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CANADIAN ASTRONAUTICS LIMITED

TP7816E

PRECISE INTEGRATED NAVIGATION SYSTEM (PINS)

Prepared for: Transportation Development Centre
Guy-Favreau Complex
200 Dorchester Blvd. West
Suite 601, West Tower
Montreal, Quebec H2Z 1X4

July 1986

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CAL Report No.: 350G-CAL-RT-10382

Prepared By: Canadian Astronautics Ltd.
1050 Morrison Drive,
Ottawa, Ontario, K2H 8K7

Authors: B. Raman & D.M. Ball

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NOTE: The contents of this report reflect the view of the contractor and not necessarily the official views or policies of the Transportation Development Centre.

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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17. Abstract

This report describes a Precise Integrated Navigation System (PINS), which will allow ships to navigate the St. Lawrence Seaway from Montreal to Kingston in dense fog or after buoys have been removed at the end of the shipping season, and thereby improve Seaway throughput. A previous study has shown that a navigation system must provide the ship's Captain with a positional accuracy of at least ± 7.6 m (±25 ft.) if it is to be adequate.

The report summarizes the system requirements, describes methods of ship location (including passive and active techniques with both ship and shore locations) and defines the tracking and display system requirements. The report also describes five systems which meet the performance requirements and provides a preliminary cost/benefit analysis of the most cost-effective system, an Image Correlation System. This system utilizes a conventional ship's radar image and correlates it with a previously stored radar image taken at a nearby precise location. The technique requires no shore based equipment and therefore costs much less than competitive techniques.

Included in the report is a description of a suitable evaluation technique.

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17. Résumé

Ce rapport décrit un système intégré de navigation de précision qui permettra aux navires de naviguer dans la voie maritime du St-Laurent, entre Montréal et Kingston, dans un brouillard épais ou après l'enlèvement des bouées, à la fin de la saison de navigation. Le système améliorera donc la sécurité de la circulation dans la voie maritime. Une étude précédente a démontré qu'un système de navigation, pour être adéquat, doit permettre au capitaine d'un navire d'obtenir une précision de position minimale de ± 7.6 m(±25 ft).

Le rapport résume les besoins du système, décrit les méthodes de localisation du navire, dont les techniques passives et actives avec l'emplacement du navire et des côtes, et définit les besoins des systèmes de repérage et d'affichage. Il décrit également cinq systèmes qui répondent aux exigences de performance, et fournit une analyse préliminaire coût/bénéfice du plus avantageux d'entre eux. De plus, il présente un système de corrélation d'images entre une image radar classique prise à bord d'un navire et une autre image radar mémorisée, prise dans un endroit précis des environs. Cette technique ne nécessite aucun équipement terrestre et coûte par conséquent beaucoup moins cher que d'autres techniques concurrentielles.

Le rapport comprend également la description d'une méthode acceptable d'évaluation.

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SUMMARY

i) Introduction

The St. Lawrence Seaway is important to the economy of Canada, primarily because marine transport is the most fuel efficient means of transporting bulk goods. However, delays in moving goods through the Seaway increase transportation costs, hence reducing Canada's competitiveness in the market place.

Two of the major causes for delays in the seaway are fog, which reduces visibility, and ice, which necessitates removal of floating navigational aids. According to the Dominion Marine Association, these delays costs the seaway traffic at least 6% of available sailing time. Reduction of this delay time could improve the Seaway throughput by 6%, with only a very modest increase in operating costs.

This report reviews the navigational accuracy, tracking, and display requirements of a Precise Integrated Navigation System (PINS), evaluates various navigation techniques and selects, on the basis of performance and cost, the optimum system.

ii) Positional Accuracy Requirements

A previous study, conducted by German and Milne, concluded that a cross-track positional accuracy of 7.6 m (2σ) and an along-track error of $\pm$12.8 m (2σ) will be sufficient for navigation through the Montreal to Kingston portion of the Seaway. The only exceptions are the St. Louis and Valleyfield bridges, which require a more accurate technique.

iii) Alternative Location Techniques

Many alternative navigation techniques are available for consideration: these techniques are evaluated on the basis of positional accuracy, possible obsolescence, long-term accuracy, vulnerability and cost.

Following is a list of navigation systems which were investigated and found to be inadequate on the basis of technical performance:

a) Differential Omega - insufficiently accurate
b) Trans it/Navsat - insufficiently accurate
c) Differential Loran - questionable accuracy and reliability
d) Laser System - not all-weather
e) Sonar System - susceptible to ice scouring
f) DME-P - insufficiently accurate
g) MF Phase Comparison - marginally usable, not sufficiently reliable
h) Shore Based Radar - too complex and not reliable
i) MLS - complex and not reliable
j) DF - insufficiently accurate

The following systems were also investigated and found to provide acceptable performance:

a) Ship's radar using image correlation,
b) Ship's radar with polarimetric reflectors,
c) Ship's radar with transponders, and
d) Radio ranging system (UHF or microwave).

Differential GPS is also likely to yield acceptable accuracy; however, it is currently not operational to the extent required and may not be before 1991.

iv) Tracking and Display Systems

A ship moving with a speed of 8.5 knots travels a distance of 8.75 m in 2 seconds, a distance which is larger than the allowable positioning error in the channel. When combined with the location system inaccuracy, the resulting error in position would make the system unusable. Since the ship's motion can be assumed to be continuous within an update interval, its instantaneous position can be predicted to a better degree of accuracy by extrapolation from the previous position information, with the help of a tracking algorithm.

An appropriate tracking filter, using smoothed position and velocity values based on ship's dynamics and motion history, is required. The ship's heading, obtained from the gyro must also be checked for consistency to ensure that the required minimum clearance is available to the shoreline from the fore and aft of the ship.

The display system must convey the position and heading information in real-time to the ship navigator. One efficient means of presenting this information is by using a graphical display, which shows a map of the channel (ie. an electronic chart) and the location and heading of the ship in the channel. It is also desirable to overlay a radar image on the electronic chart in order to continuously monitor the positioning system performance as well as observe other ships in the vicinity. Other information such as heading, course line, speed, distance to next waypoint, etc, must also be displayed.

v) Selected System

Of the four systems found technically acceptable, it was determined that three could be eliminated because of higher costs due to the requirement for shore installations. The fourth, the image correlation system, does not require shore-based equipment and is based on the existing shipboard radar. While the system does require the preparation of a reference radar image file, it was concluded that this file would not be extremely expensive to prepare and that updates would seldom be required.

The image correlation technique (or clutter mapper) compares the image produced by the ship's radar with one of several stored radar images obtained at several calibrated reference points along the course line, and computes the displacement vector with respect to a particular reference point. The comparison of the two images is done by correlation. The ship's

radar image is displaced pixel by pixel in the X and Y directions and the correlation coefficient is computed for each displaced position. The displacement vector, which produces the maximum value for the correlation coefficient, gives the position of the ship relative to the reference point. The position is refined by finding the centre of gravity for a matrix of correlation coefficients, thereby obtaining a resolution better than the basic pixel resolution. (The calculated correlation coefficient is a measure of confidence in the correlation process and could also be displayed to the operator.)

If the ship speed is assumed as 5 knots, and the scan update time for the ship's radar is two seconds, then the ship moves by about 5.14 m in one update period. If the pixel resolution is assumed as 7.5 m, the ship's movement is about one pixel for each update. By using a resolution of 512 by 512 pixels for the reference image, a radius of 1.92 km can be covered by a single reference image. For a 50 percent overlap between adjacent reference images, (ie. length of course line equal to 1.92 km) and a total course line length of 300 km, 157 reference images will be required. In order to better accommodate sharp turns and different viewing aspects (effect of blockage by ships, etc), a total of 200 reference radar images are assumed to be required. The reference images can be stored on a compact laser disc as disc files and retrieved by the processor whenever required. The size of each disc file is 512 x 512 and for 200 images, a total capacity of 52.5 M pixels is required. A pixel resolution of 4 bits is assumed; therefore, the memory requirement is 0.21 gigabits.

Each computation of the correlation coefficient requires 256 x 256 multiplications and additions. The system first computes the correlation coefficient using a displacement approximated by the prediction algorithm used for tracking. Next, the image is shifted around this mean position, and correlation coefficients are computed for each shift. A correlation coefficient matrix of either 3 x 3 or 5 x 5 may be computed, centered around the first computation. Assuming a worst case 5 x 5 matrix or 25 computations of the correlation coefficient, a total of 25 x 256 x 256 or 1.64 million multiplications and additions must be performed for each update. The position of the centre of gravity is then computed from the matrix of correlation coefficients and declared as the ship's location.

The correlation technique will not work well in areas of open water, where most of the image is devoid of features. Since correlation is mainly useful for features on land, the area covered by water may be masked from correlation. This approach also avoids clutter in the near range of the ship, for which the radar receiver is saturated and therefore of little value. When using the correlation technique in larger lakes, it is desirable to offset the image correlation so that the comparison covers mostly land features rather than open water. This could best be done by splitting the image into two halves such that each half covers the land area close to the shoreline on either side of the lake. In narrow reaches which involve sharp turns, it will be necessary to have more reference images in order to account for shadowing by tall vertical features such as cliffs or heavily treed islands.

vi) Conclusions and Recommendations

This study concludes that the image correlation system is the most cost effective solution to aid navigation of a ship through the St. Lawrence Seaway under adverse conditions. The approach requires no shore based equipment, utilizes the existing marine radar, and the only other requirement is preparation of about 200 reference digital radar images.

As this system has been shown to be fundamentally sound, it is recommended that development be continued with a system test in the Seaway. This may be done best by providing a prototype image correlation system for the radar on a ship currently regularly using the Seaway, adding a tracking filter, producing a set of reference images stored in digital form for a portion of the Seaway, and then proceeding to test the system, with special attention given to the effects of heavy rain.

The final test would involve using a reference radar image generated using one ship to steer a second ship through the same area, thereby confirming the system's ability to provide the required accuracy for multiple users. These demonstrations provide the necessary proof that the system supplies the required accuracy, is adaptable to a Seaway ship, operates under adverse environmental conditions, and as a consequence, will improve Seaway throughput.

SOMMAIRE

i) Introduction

La Voie maritime du Saint-Laurent joue un rôle important dans l'économie canadienne surtout parce que le transport maritime est de tous les modes de transport de vrac celui qui présente le meilleur rendement énergétique. Toutefois, les nombreux retards dans la Voie maritime font augmenter les coûts de transport au détriment de la compétitivité des produits transportés et, par conséquent, du Canada lui-même sur les marchés internationaux.

Les deux principales causes de retard dans la Voie maritime sont le brouillard qui réduit la visibilité, et la glace qui nécessite l'enlèvement des aides flottantes à la navigation. Selon la Dominion Marine Association, ces retards y réduisent d'au moins 6% la période de navigation. Éliminer ce problème permettrait d'améliorer d'autant la capacité de transport, avec une très minime augmentation des coûts d'exploitation.

Le présent rapport analyse les caractéristiques de précision de navigation, de repérage et d'affichage à exiger d'un système intégré de navigation de précision, évalue diverses techniques de navigation dans l'optique de navigation envisagée et choisit le système optimal en termes de performance et de coûts.

ii) Exigences en matière de précision de position

Une étude antérieure effectuée par German et Milne a révélé qu'une précision transversale de 7,6 m (2σ) et axiale de $\pm$12,8 m (2σ) est suffisante pour naviguer dans la voie maritime entre Montréal et Kingston. Les seules exceptions étant les ponts de St-Louis et de Valleyfield où il faut une plus grande précision.

iii) Techniques de localisation envisageables

Un certain nombre de techniques peuvent être envisagées. Ce rapport les évalue en fonction des paramètres suivants: degré de précision de position, obsolescence possible, précision à long terme, vulnérabilité de l'équipement et coût.

Les systèmes de navigation suivants ont été écartés en raison de performances techniques insuffisantes:

a) Omega différentiel - manque de précision
b) Trans it/Navsat - manque de précision
c) Loran différentiel - précision et fiabilité douteuses
d) Système Laser - sensibilité aux perturbations météorologiques
e) Système Sonar - susceptible d'être endommagé par la glace
f) Système DME-P - manque de précision
g) Système de Comparaison de phase MF - partiellement utilisable, peu fiable
h) Radar terrestre - trop complexe et non fiable
i) Système MLS - complexe et non fiable
j) Système RG - manque de précision.

Par contre, les systèmes suivants ont affiché une performance acceptable:

a) Radar de bord avec corrélation d'images
b) Radar de bord avec réflecteurs polarimétriques
c) Radar de bord avec transpondeurs, et
d) Système radiotélémétrique (UHF ou hyperfréquence).

Le système différentiel de positionnement global donnera probablement des degrés de précision acceptables, mais il n'est pas encore opérationnel pour ce qui concerne l'application envisagée ici et ne le sera probablement pas avant 1991.

iv) Systèmes de poursuite et d'affichage

Un navire qui se déplace à une vitesse de 8,5 noeuds couvre une distance de 8,75 m en 2 secondes. Cette distance est plus grande que l'erreur de position admissible dans la voie de navigation. Cet écart ajouté à l'imprécision du système de localisation, rend le système inutilisable. Puisque le mouvement du navire peut être supposé continu pendant une péroide de balayage, il est possible de prédire la position instantanée du navire avec plus de précision en faisant une extrapolation d'après les renseignements de la position antérieure à l'aide d'un algorithme de poursuite.

Il sera nécessaire d'adopter un filtre de poursuite approprié, utilisant des courbes lissées de position et de vitesse basées sur les caractéristiques dynamiques du navire et les données historiques de comportement. Le cap doit également être surveillé continuellement pour vérifier qu'il concorde avec les données gyroscopiques et assurer que la proue et la poupe du navire ne sont pas trop proches du rivage.

Le système d'affichage doit indiquer en temps réel les données de position et de cap au navigateur. L'affichage graphique constitue un moyen efficace pour présenter cette information puisqu'il permet de visualiser la position et le cap du navire sur une carte de las voie (carte électronique). Il est éminamment souhaitable de superposer une image radar sur la carte électronique afin de contrôler continuellement la performance du système de positionnement et d'observer les autres navires dans les environs. D'autres informations comme le cap, la route, la vitesse, la distance au prochain point de contrôle, etc., doivent également être affichés.

v) Systèmes choisis

Des quatre systèmes jugés techniquement acceptables, trois ont été éliminés en raison du coût élevé des installations terrestes requises. Le quatrième, soit le système de corrélation d'images, ne nécessite aucun équipement terrestre puisque son fonctionnement repose sur le radar de bord, et même s'il nécessite la préparation d'un dossier d'images radar de référence, les spécialistes pensent que la composition d'un tel dossier ne serait pas extrêmement onéreuse et que les mises à jour seraient peu fréquentes.

La technique de corrélation d'images consiste à comparer l'image prise par le radar de bord à l'une des nombreuses images radar mémorisées représentant des points de référence aux coordonnées parfaitement connues le long du trajet, et de calculer le vecteur de déplacement par rapport à un point de référence donné. La comparaison entre les deux images se fait par corrélation. L'image radar de bord est déplacée pixel par pixel dans les directions X et Y et le coefficient de corrélation est calculé pour chacune des diverses positions. Le vecteur de déplacement qui produit le plus grand coefficient de corrélation donne la position du navire par rapport au point de référence. La position est affinée en trouvant le centre de gravité d'une matrice de coefficients de corrélation. De cette manière, on obtient une résolution supérieure à la résolution de base par pixel. (Le coefficient de corrélation calculé étant une indication de la fiabilité du processus de corrélation, il pourrait également être utile de l'afficher à l'intention de l'opérateur).

En supposant que le navire se déplace à une vitesse de 5 noeuds et que la période de balayage du radar de bord est de deux secondes, alors il franchit environ 5,14 mètres par période. De plus, en supposant que la résolution par pixel est de 7,5 m, le déplacement du navire correspond à environ un pixel pour chaque période de balayage. En utilisant une résolution de 512 x 512 pixels pour l'image de référence, on peut couvrir un rayon de 1,92 km avec une seule image de référence. Pour un recouvrement de 50% entre les images de référence adjacentes, (donnant une longueur axiale égale à 1,92 km) et une longueur axiale totale de 300 km, il faudra donc 157

images de référence. Afin de mieux voir les virages prononcés et les divers points de vue (effet de blocage par les navires, etc.), on estime qu'il faudrait produire un total de 200 images de références. Ces images peuvent être stockées sur disque laser compact sous forme de fichiers-disques et récupérées par le processeur selon les besoins. Le format de chaque fichier-disque étant de 512 x 512, if faudrait une capacité totale de 52,5 M pixels pour 200 images. En supposant que la résolution d'un pixel requiert 4 bits d'information, la mémoire devrait avoir une capacité de 0,21 gigabits.

Chaque calcul du coefficient de corrélation nécessite 256 x 256 multiplications et additions. Le système calcule d'abord le coefficient de corrélation à partir du déplacement donné approximativement par l'algorithme prévisionnel utilisé pour la poursuite. Ensuite, l'image est déplacée autour de sa position moyenne, et des coefficients de corrélation sont calculés pour chaque déplacement. Une matrice de coefficients de corrélation de 3 x 3 ou de 5 x 5 peut être calculée et centrée autour du premier calcul. En supposant le cas extrême d'une matrice de 5 x 5 ou de 25 coefficients de corrélation, un total de 25 x 256 x 256 ou 1, 64 M multiplications et additions doivent être effectuées pour chaque période de balayage. La position du centre de gravité est ensuite calculée à partir de la matrice des coefficients de corrélation et établie comme étant la position du navire.

La technique de corrélation sera difficilement applicable en eau libre, où l'image est dépourvue de caractéristiques. Étant donné que la corrélation est essentiellement utile pour les caractéristiques terrestres, rien n'interdirait de soustraire les surfaces d'eau libre à la corrélation. Cette méthode permet d'éviter les retours parasites à proximité du navire qui ne font que saturer le récepteur radar dont les données n'ont alors que peu de valeurs. Lorsqu'on utilise la technique de corrélation dans les lacs plutôt grands, il est souhaitable de décaler la corrélation d'images de sorte que la comparaison comprenne essentiellement des caractéristiques terrestres plut que de l'eau libre. La meilleure façon de procéder consiste à couper l'image en deux parties, de façon que chacune d'entre elles couvre la bande de terre près du rivage de chaque côté du lac. Dans les passages étroits comportant des virages prononcés, il sera nécessaire de se servir d'un nombre plus grand d'images de référence pour tenir compte des ombres causées par de grandes caractéristiques verticales, notamment des falaises ou des îles fortement boisées.

vi) Conclusions et recommandations

L'étude permet de conclure que le système de corrélation d'images constitue la solution la plus économique de navigation dans la voie maritime du St-Laurent. Cette technique ne nécessite aucun équipement terrestre puisqu'elle utilise le radar de bord, la seule contrainte étant la préparation d'environ 200 images radar numériques de référence.

Le système s'étant révélé fondamentalement sûr, on recommande la poursuite de son développement à l'aide d'un système pilote dans la voie maritime. Il s'agirait en fait d'adjoindre un corrélateur d'images prototype au radar de bord d'un navire qui emprunte régulièrement la Voie maritime, d'ajouter un filtre de poursuite, de produire un jeu d'images numériques de référence pour une partie de la voie maritime et de procéder ensuite à l'essai du système, en portant une attention particulière aux effets causés par les fortes pluies.

L'essai final consisterait à utiliser une image radar obtenue par un navire pour en diriger un autre dans le même secteur. Cela permettrait de confirmer la capacité du système à assurer la précision requise pour desservir plus d'un utilisateur à la fois, que le système est en mesure d'assurer cette précision, qu'il est adaptable aux navires empruntant la Voie maritime, qu'il fonctionne dans des conditions environnementales extrêmes et, par conséquent, qu'il améliorerait la circulation dans la Voie maritime.

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1.0 INTRODUCTION

The St. Lawrence Seaway is important to the economy of Canada, primarily because marine transport is the most fuel efficient means of transporting bulk goods. However, due to delays in movement through the seaway, other less economical forms of transport, i.e. rail and truck, are often substituted, thereby reducing the commodity's and Canada's market competitiveness. Two of the major reasons for delays in the seaway are:

- Fog, which reduces visibility to an "unsafe to proceed" level.
- Ice, which necessitates removal of floating navigational aids, limits movement.

According to a Dominion Marine Association study conducted in 1981 [1], these delays costs the seaway traffic at least 6% of available sailing time. Elimination of this delay time would therefore improve the Seaway throughput by 6%, with only a very modest increase in operating costs.

The problem of sailing a ship through a narrow channel is solvable; however, the solution must be both cost-effective and easy to use by the ship's personnel. This study evaluates various techniques to solve this problem, selects the most promising technique or techniques on the basis of performance and cost effectiveness, and describes by means of a functional block diagram the key constituents of the solution or solutions.

The study includes the following sections:

1) Requirements - provides a review of the navigational position accuracy requirements along the Seaway. (based on documents by German and Milne and discussions with Captain Fisher.)

2) Location Techniques - includes a study of all relevant methods of ship location including both passive and active techniques and shipboard and shore configurations. Optimum solutions, with respect to relative position accuracy, relative cost and relative reliability, are selected for applicability.

3) Tracking/Display Systems - provides a study of the tracking techniques required to maintain a continuous positioning indication, plus a study of the suitable display means with respect to accuracy, response time, convenience of usage and value to the operator.

4) System Configuration - provides block diagrams and a more detailed description of the requirement for each of the systems which were found to meet the technical requirements. A relative costing exercise compares the systems and defines the most cost effective, concluding with a preliminary cost estimate for the selected system.

5) Conclusions and Recommendations - provision of a summary of recommendations, describing suitable evaluation techniques to substantiate the value of the system to ship owners.

2.0 SYSTEM REQUIREMENTS

The St. Lawrence and Great Lakes system extends 3200 km from Sept Iles to Thunder Bay and is used by about 175 vessels belonging to members of the Dominion Marine Association ,together with an approximately equal number of deep sea ships and a somewhat smaller number of U.S. carriers [1]. This activity might be expected to grow, since marine transport, being the most efficient form of bulk carrier, is much less affected by increase in fuel costs compared to other forms of transport. This study will consider alternative navigation systems for the Montreal-Kingston section of the Seaway.

A definition of positioning accuracy requirements and display requirements for a Precise Integrated Navigation System (PINS) for the Montreal to Kingston sector of the seaway is available in the report prepared by German & Milne Inc. of Ottawa [2].

Implementation of PINS can be based on several basic techniques, i.e.:

a) intelligence on shore with precision ranging techniques, and data transmitted to the ship, or

b) intelligence aboard the ship using GPS, Loran, radar, or other means, or

c) a combination of the two.

2.1 POSITIONAL ACCURACY REQUIREMENTS

The required system accuracy for the Montreal to Kingston portion of the Seaway depends on the ship's characteristics, nature of the channel and environmental conditions. The previous German and Milne report included an analysis for a channel of width between 137 m (450 ft.) and 183 m (600 ft.), which resulted in the selection of a position error requirement of ±7.6 m (±25 ft.) The minimum channel width condition is not satisfied at St-Jean and Valleyfield bridges, which have a width of only 55 m (180 ft.) A more accurate positioning technique will be required at these locations, for instance, they could be treated as locks.

Typical maneuvering situations for ships of 223 m (730 ft.) length and 23 m (75 ft.) beam, discussed in [2], are shown in figures 2.1, 2.2, and 2.3. The findings were as follows:

a) A cross track positioning error not exceeding ±7.6 m (± 25 ft.) would allow a ship 223 m length and 23 m beam to negotiate a 137 m wide channel and maneuver under reasonable environmental conditions.

b) Two ships of the above size may be allowed to pass in opposing directions in a straight section of 183 m (600 ft.) wide channel provided each knows the position and aspect of the other.

c) Along track error based on 1 second update and 10 knot speed should not exceed ±12.8 m (42 ft) for both cases (a) and (b).

The German & Milne report recommends a cross track position error of ±7.6 m (25 ft.) 2 standard deviations (95%) and an along track error of ±12.8 m (42 ft.) 2 standard deviations (95%) to be adopted for PINS. Decreasing these error bounds by any given amount would allow a reduction in the channel width by the same amount, with the assumed tolerances for maneuvers. It is assumed, for the purposes this study, that the ship's heading information is obtained from the ship's gyro at a 1 Hz update rate.

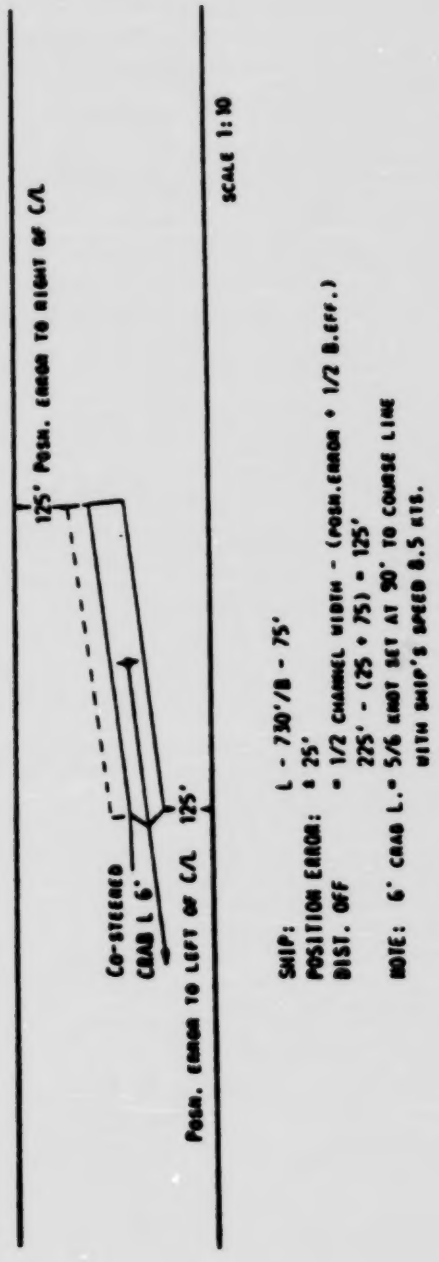

125' POSN. ERROR TO RIGHT OF C/L
SCALE 1:10
CO-STEERED
CRAB L 6°
125'
POSN. ERROR TO LEFT OF C/L
SHIP: L - 730'/B - 75'
POSITION ERROR: = 25'
DIST. OFF = 1/2 CHANNEL WIDTH - (POSN.ERROR + 1/2 B.EFF.)
225' - (25 + 75) = 125'
NOTE: 6° CRAB L.= 5/6 KNOT SET AT 90° TO COURSE LINE
WITH SHIP'S SPEED 8.5 KTS.

Figure 2.1 Single Ship in 137 m Wide Channel [2]

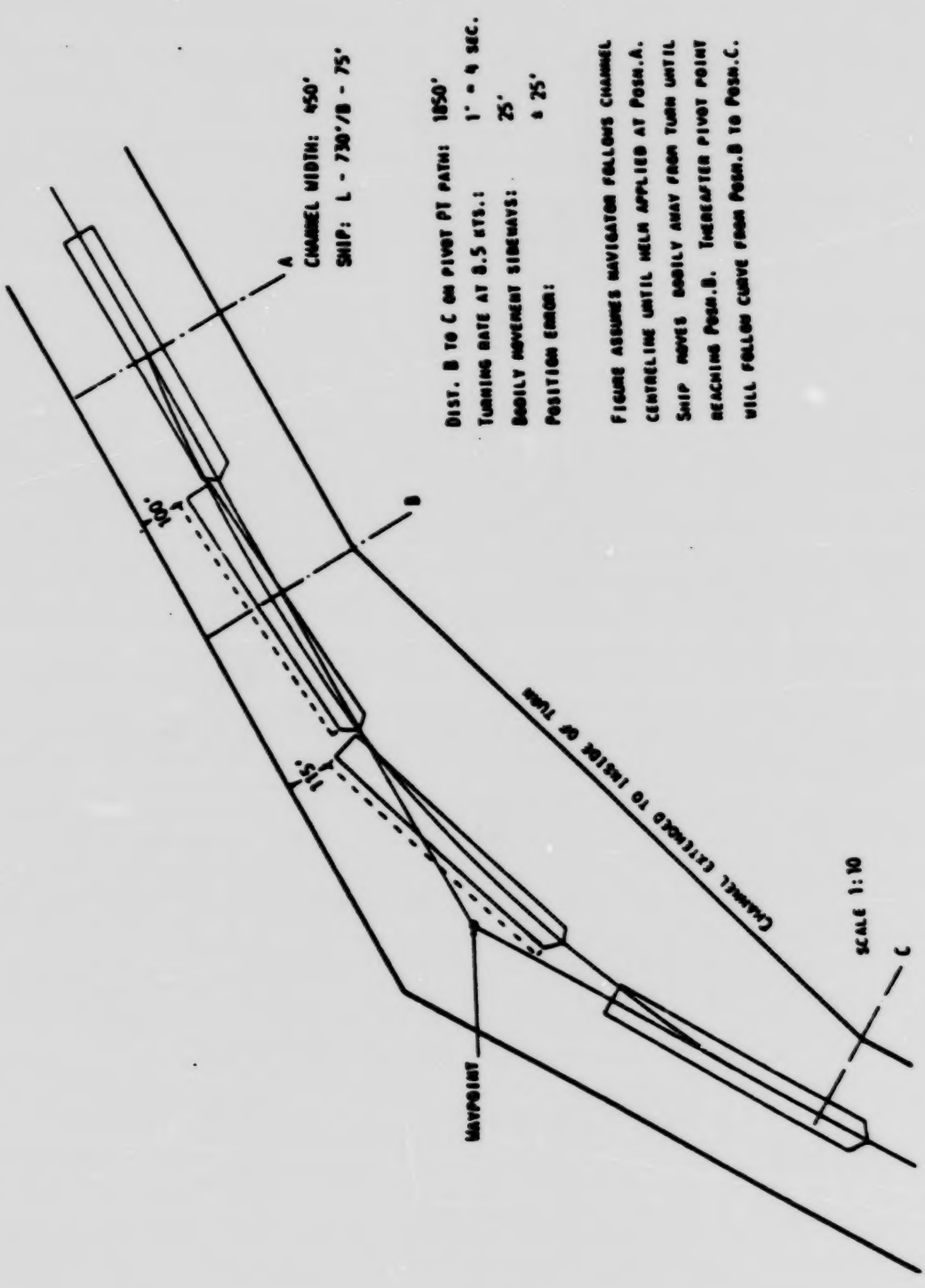

CHANNEL WIDTH: 450'
SHIP: L - 730'/B - 75'
DIST. B TO C ON PIVOT PT PATH: 1850'
TURNING RATE AT 8.5 KTS.: 1° = 4 SEC.
BODILY MOVEMENT SIDEWAYS: 25'
POSITION ERROR: ± 25'
FIGURE ASSUMES NAVIGATOR FOLLOWS CHANNEL CENTERLINE UNTIL HELM APPLIED AT POSN.A. SHIP MOVES BODILY AWAY FROM TURN UNTIL REACHING POSN.B. THEREAFTER PIVOT POINT WILL FOLLOW CURVE FROM POSN.B TO POSN.C.
A
B
C
100'
115'
CHANNEL EXTENDED TO INSIDE OF TURN
SCALE 1:10
WAYPOINT

Figure 2.2 Approximate Path Of Ship Making Turn [2]

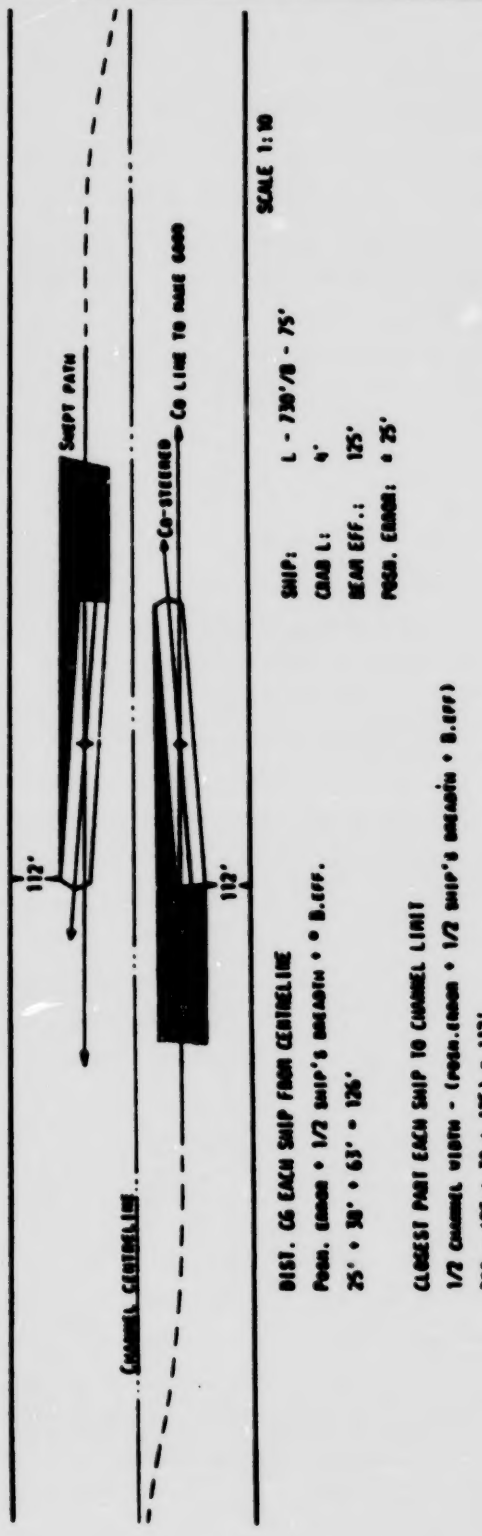


Figure 2.3 Ships Passing in 183 m Channel [2]

2.2 DISPLAY REQUIREMENTS

A visual display, representing navigational information in the form of digital readouts and preferably a graphical representation of the channel indicating the ship's location in the channel and surrounding geographical features, is required as part of a Precise Integrated Navigation System (PINS). This information, derived from different sensors, must be integrated and presented in a suitable way that helps the navigator to exercise judgement on where to place the ship in the channel, what speed to proceed, when to commence a turn, etc.

The type of information required on a digital readout is given in Table 2.1 and the nature of a graphic display is illustrated in Figure 2.4 [2]. The minimum distance to channel limit information shown in Table 2.4 must take into account the maximum possible error of 2.3 m (7.6 ft.) to the right or left of the course line and indicate the distance off from the nearest point on the ship to the channel limit.

Instead of displaying "ships head up" as is done in the ships radar, the channel course line should be displayed vertically up, so as to avoid picture skewing due to course changes within the channel, for the occupied reach. The outline of the ship shown to scale in the display of Figure 2.4 will have its effective beam increased by 15.1 m in order to allow for the system error. Several scales such as ½, 1 and 3 nautical miles would be necessary. The display should be up-dated at an interval not greater than two seconds so as to indicate smooth transitions.

The above requirements are considered as basic requirements for the PINS. In addition, it would be helpful to provide an overlay of the radar image on top of the graphic display, as an option which can be turned on or off. This would help in visually checking the performance of the system against the radar output, and in locating other ships within line of sight in the channel. Another feature that can be added is a display of the ship's course by marking its position at discrete intervals, thereby indicating its past history of movement along the channel. Since the display resolution is limited, a zoom feature, with different full scale ranges, would be very desirable.

Table 2.1 Digital Readout

PARAMETER	UNITS	SOURCE
Channel course line	Degrees true	stored data
Ship's head	Degrees true	ship's Gyrc
Speed over ground	Knots and tenths	Computed (from position)
Distance to next Waypoint	Nmi and Tenths	Computed
Time to next waypoint	Minutes and tenths	Computed
Course line next reach	Degrees true	Stored Data
Minimum distance to channel limit	Left:	Computed
	Right:	Computed

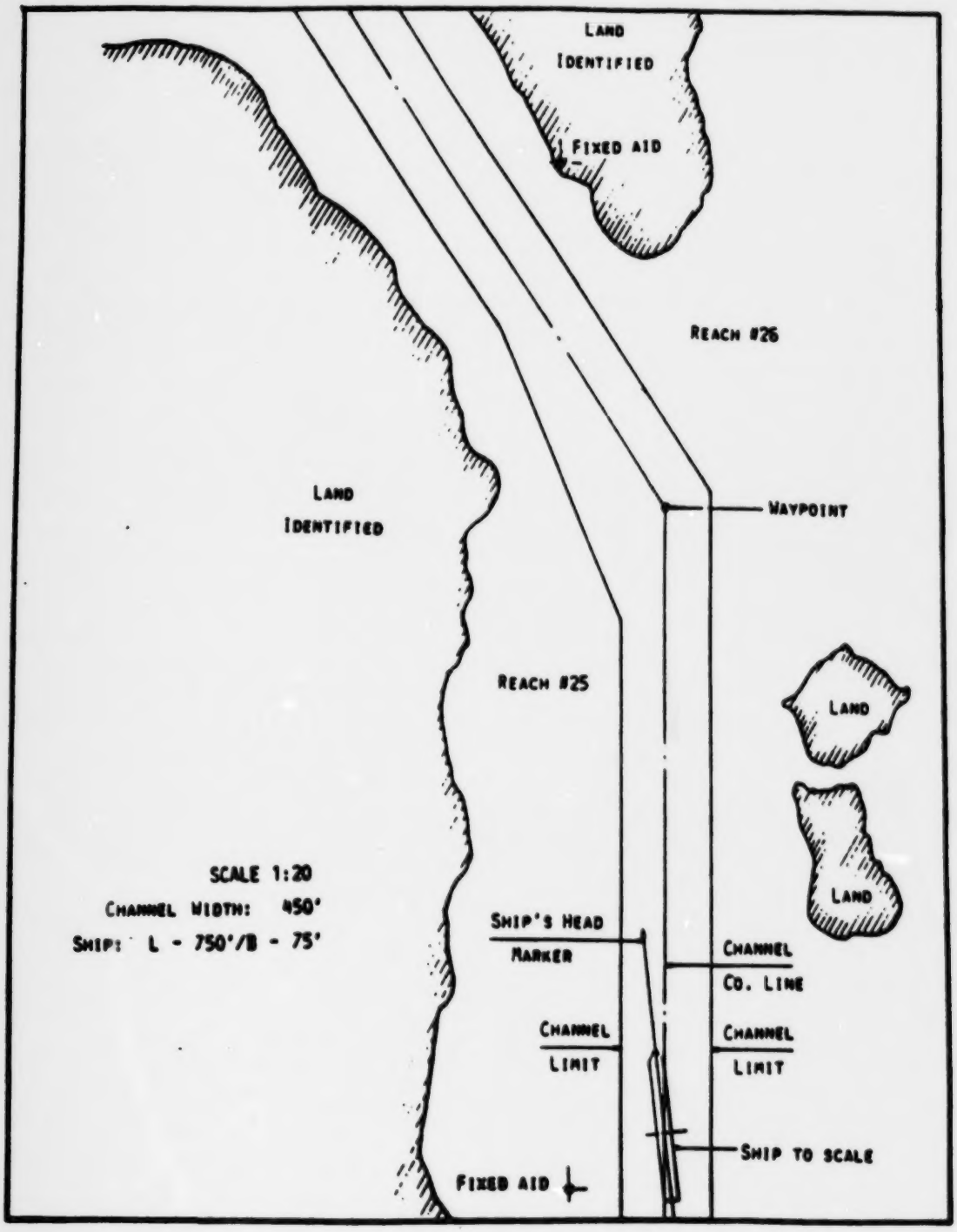


Figure 2.4 Display Graphical Format

2.3 OPERATIONAL CONSIDERATIONS

The positioning accuracy specified in section 2.1 is the required dynamic accuracy of the system, when the ship is moving at a specified maximum speed. The system accuracy must also take into account the effect of errors in the ship's heading, which is measured by the ship's gyro. In the event of system malfunction or degradation, the system must be capable of providing a warning signal, so that necessary action can be taken.

2.3.1 MOTION ERRORS

The dynamic positioning accuracy that can be achieved with a positioning system depends on several additional factors, such as the ship's cruising speed, the system update rate, the magnitude and direction of the current, environmental factors and the control input given to the ship, besides the static positional accuracy that is obtainable from the system. The required static positioning accuracy may be computed, neglecting all the factors except the ship's speed and the system update rate.

As an example, the ship's maximum speed under poor visibility conditions is assumed as 5 knots (with 2 knot current and 3 knots for steering) and the system update interval is assumed as 2 seconds. Within the update interval, the ship moves by a distance of 2.57 m. The maximum along track error can be 5.14 m, if no tracking and prediction were used for calculating the ships position. The value of the cross track error depends on the angle θ, between the ship's velocity vector v_s and the channel course line (Figure 2.5). If the maximum value of θ is θ_{max}, the maximum cross track error is $(v_s \text{ Sin } \theta_{max})t_u$, where t_u is the update time interval. If θ_{max} is assumed as 5 degrees (worst case scenario), the maximum cross track error is 0.45 m.

2.3.2 HEADING ERRORS

The ship's heading is normally measured by the ship's gyro, which produces a continuous electrical output. The accuracy of the gyro is assumed to be 0.5 degree worst case, typically 0.25°. The effect of this error is to increase the effective beam of the ship, thereby reducing the clearance available in the channel. For a 223 m long ship, the effective worst case reduction in the across track clearance is equal to 223 Sin (0.5) or 1.95 m.

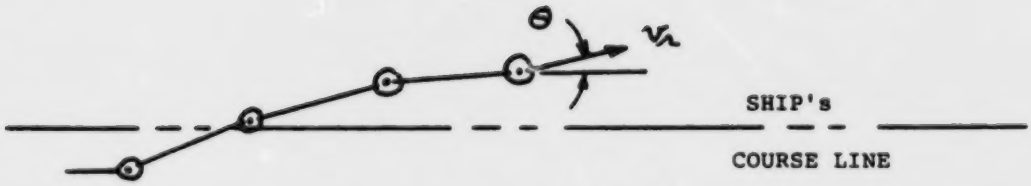


Figure 2.5 Errors Due to Ship's Motion

Any along-track error in the ship's location affects the angle to be set for the ship's heading. This is not relevant at straight sections of the channel but becomes important while negotiating turns. For example, if a turning rate of 1 degree in 6.8 seconds is assumed at 5 knots, and the turning distance is 564 m, (1,850 ft.), as shown in Figure 2.2, a 32 degree turn is executed in 219 seconds. If the ship had turned half this angle (16 degrees) before reaching the waypoint, then an along track position error of x metres would reduce the clearance at the rear of the ship by x Sin 16°. For x equal to 5 m, this error would be about 1.38 m.

2.3.3 STATIC ACCURACY

With considerations for dynamic errors, in order to achieve cross track and along track dynamic accuracies of 7.6 m (25 ft.) and 12.8 m (42 ft.), the positioning system must be capable of providing static accuracies of 3.91 m and 8.43 m respectively, in the two directions. This is computed as shown below:

Required Static Accuracy = Required Dynamic Accurancy - Sum of all the errors.

	Cross Track (m)	Along Track (m)
Required dynamic accuracy	7.62	12.80
Motion error	0.38	4.37
Heading error	1.95	0
Turning error	1.38	0
Therefore, required static accuracy	3.91	8.43

There is no allowance here for system failure. The impact of failure is discussed in the following section.

2.3.4 SYSTEM FAILURE

In order to ensure operational safety, the system must continuously monitor its own performance and raise an alarm when it detects a failure or degradation of performance. This may be accomplished by using on-board calibration techniques and checking for data consistency. The system must check all measured and computed parameters against set maximum limits and causing a warning signal if any of these parameters go out of bounds. Redundant systems might also be used in order to improve the performance reliability. The maximum delay that can be tolerated between the occurrence of a failure and the alarm indication depends on the maximum time that can be allowed to take necessary action and maneuver the ship to safety, in the event of system failure.

This delay cannot be shorter than the system update time since this is the minimum time required for data acquisition and computation of all the parameters. For example, if the distance to stop the ship is assumed to be one ship length (223 m or 730 ft.) and the speed of the ship at the time of failure as 5 knots, the stopping time is 83 seconds.

The maximum delay should be no more than 10% of this, or less than 8.3 seconds. Therefore a system update rate of 2 seconds or less is recommended, assuming two updates are required, one to detect a failure, the second to confirm the failure.

3.0 LOCATION TECHNIQUES

Radionavigation systems may be broadly classified as long-range and short-range systems. Long-range systems such as Loran-C, Decca, Omega, and Transit are predominantly used for marine navigation, whereas short-range line of sight systems such as VOR/DME and ILS are used mainly for aviation. Table 3.1 lists the main radionavigation systems currently used and the estimated number of users [3].

The navigation systems given in Table 3.1 for marine usage do not have sufficient accuracy, as stand-alone systems, for channel navigation. More recently several precise integrated navigation systems are being developed, using differential Loran, differential GPS, ship's radar etc., in order to obtain improved accuracies in estimating the instantaneous position of the ship.

The choice and development of PINS must take into account the following operational requirements, listed in the order of priority:

(1) Accuracy (Inherent) - Short Term

The required positional accuracy in both the along track and cross track directions must be satisfied. In addition, the ship's heading must be measured to the required accuracy.

(2) Obsolescence

The possibility of a system phase out in the future must be considered, primarily for global navigational systems. There is also an element of risk in choosing a system which is being planned for the future, but is yet to be approved.

(3) Accuracy (Repeatability) - Long Term

The degree of confidence in the performance of the system must be high. The system must be able to continuously monitor its performance and raise an alarm in case of malfunction or degradation of performance.

Table 3.1 Main Radionavigation Systems of the World [3]

MAIN RADIONAVIGATION SYSTEMS OF THE WORLD

System	Frequency	Estimated Users	
		Air	Marine
Omega	10–13 kHz	10 600	7000
Loran-C	90–110 kHz	1000	60 000
Decca	70–130 kHz	1000	30 000
Beacons/DF*	200–1600 kHz	200 000	500 000
ILS*	75, 108–112, 329–335 MHz	70 000	–
VOR*	108–118 MHz	200 000	–
Transit	150, 400 MHz	–	38 000
Tacan	960–1215 MHz	17 000	–
DME*	960–1215 MHz	80 000	–
SSR*	1030, 1090 MHz	100 000	–
MLS*	5031–5091 MHz	implementation about to start	
Doppler	13 GHz	5000	

*Signal format standardized by the International Civil Aviation Organization.

(4) Vulnerability due to Interference

The vulnerability of the system to physical and natural effects must be minimal. This includes effects such as multipath, radio interference (within the system), propagation and weather effects.

(5) Cost

This includes the cost of the basic location system, cost of redundant units to perform to a specific reliability (or availability) figure, cost of a tracking system, cost of enhancement to make it easily useable by the ship's navigator, maintenance costs, and cost of additional requirements such as interference rejection, etc.

3.1 LONG-RANGE SYSTEMS

Long-range area coverage systems include shore-based systems such as Omega, and Loran-C as well as satellite-based systems such as Transit and GPS.

3.1.1 OMEGA

Omega is a very-low-frequency (VLF) radionavigation system, operating between 10 and 14 KHz, which provides continuous global coverage for ships and aircraft using eight ground stations. It is a hyperbolic navigation system based on phase difference techniques with a realizable fix accuracy on the order of 1 to 2 nmi circular error probable (CEP) [4]. The problems associated with use of Omega include variations due to ionospheric fluctuations and the need for dead-reckoning because of inherent ambiguities in phase measurement. Combined Omega-NAVSAT receivers are used to obtain accurate position fixing during a satellite pass and dead-reckoning is used between passes. This requires accurate knowledge of the velocity of the ship over the earth, in order to assess Doppler counts during a satellite pass as well as for dead-reckoning. Omega systems for aircraft operations have multifrequency reception of all available Omega signals, and with inputs of true air speed and heading, use a Kalman filter for dead-reckoning. The multifrequency fix accuracy is about 0.9 to 1.2 nmi CEP.

Since the accuracy is mostly limited by day-to-day fluctuation in the propagation medium, two receivers in the same area exhibit similar errors. Therefore, differential Omega systems, which use spatial correlation to improve the nominal system accuracy, can be used to improve accuracy.

Repeatability in VLF systems is affected by random variations in the ionosphere or ground and over long paths by noise due to electromagnetic signals such as lightning. Coverage may also be affected by signal self-interference due to contamination with higher order modes or long path signals propagating around the world. In such cases, it becomes necessary to avoid strong signals whose phase information is not reliable. A VLF error mode data base is incorporated in coverage diagrams and Predicted Propagation Corrections (PPC's) are included as an elaborate coverage guidance software in the case of automated systems. Since the required positional accuracy is not met even by the differential mode of operation, Omega is not considered suitable for channel navigation.

3.1.2 TRANSIT/NAVSAT

Transit or NAVSAT is a U.S. Navy satellite system which is used by several marine operators and fisherman. It does not have operational status outside of U.S. Navy at present, and is scheduled for phase-out by 1992 in favour of the GPS. The NAVSAT system may be kept alive in future by the European Space Agency (ESA), if the programme is approved in 1987 [5].

The recently proposed ESA NAVSAT configuration consists of 12 satellites in elliptic 12-hour orbits inclined at 64°, in three orbital planes. In addition, six navigation payloads would be carried by communications or meteorological satellites in geostationary orbit. The total cost of this programme is approximately $1 billion with an operating cost per year of $155 million. NAVSAT Doppler mode will be used for slow-motion positioning with an accuracy of 60-100m. Used in conjunction with a ranging receiver, providing continuous pseudorange derived navigation, positioning accuracies of 5 to 25 m can be obtained for fast moving vehicles.

Due to the limited availability of the system currently used, with an update time of the order of several hours, uncertainty of its future, vulnerability in critical times and inadequacy of its positioning accuracy, Transmit is not considered suitable for seaway navigation.

3.1.3 LORAN-C

A chain of Loran-C stations transmit synchronized pulse signals at a common repetition rate, with one station designated as the master and the others as secondaries. By measuring the time difference between the master and a secondary station X, a hyperbolic line of position is established. A similar measurement between the master and another secondary station Y establishes a second hyperbolic line of position, and the receiver location is obtained as the intersection of the two lines. The operating frequency is 100 KHz and with a receiver phase measurement accuracy of .001 to .01 cycle, a timing accuracy of 10 to 100 nsec is obtained.

Geometry is an important factor in Loran-C accuracy, since the crossing angles of the hyperbolic lines diverge as the receiver moves away from the area between the stations, giving rise to a Geometrical Dilution of Position (GDOP). The GDOP for a configuration with a master station and three secondaries X,Y, and Z is illustrated in Figure 3.1 as Circular Error Probability (CEP) contours in metres for a 0.1 μs standard deviation line of position error [6].

The operational accuracy of Loran-C is also affected by propagation effects such as:

(a) propagation variations through the atmosphere,

(b) propagation over sea-water, and

(c) propagation over terrain of various conductivities and profiles.

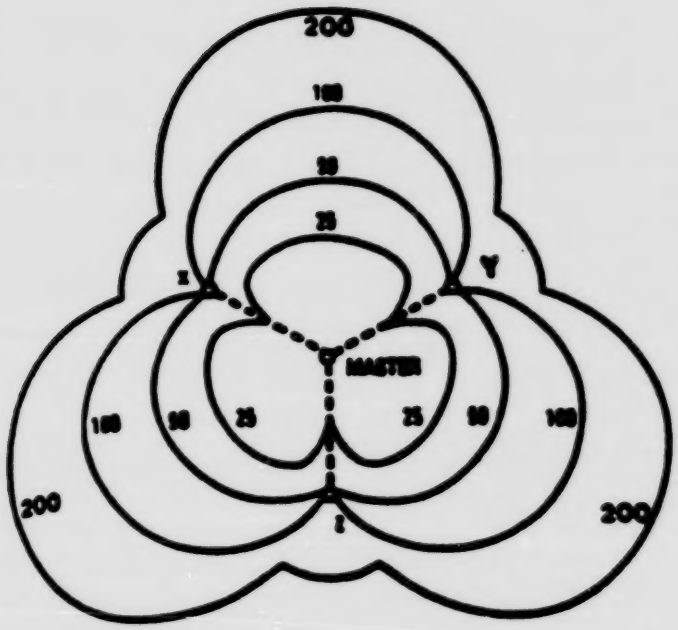


Figure 3.1 Fix Accuracy - CEP Contours in Meters for 0.1μs Standard Deviation Line of Position Error, illustrating Geometric Dilution of Position (GDOP)[6]

The effective phase velocity of the wave is a function of the path as well as weather conditions. Weather effects can produce errors on the order of 0.1 μs for 1000 km paths. In terrestrial and harbour applications of Loran-C, reradiation or scattering of signals from overhead bridges and power lines as well as interference from power line carrier communications in the 10-490 KHz band are additional problems [6]. The Department of Transportation states, in its Federal Radionavigation Plan [7, Vol. III], that Loran-C provides a predictable accuracy better than 0.25 nmi (460 m) and a repeatable accuracy of between 18 and 90 meters.

The development of portable atomic standards for precision time keeping has enabled the use of Loran-C in a one-way ranging mode ("rho-rho" mode) where only two transmitters are required for a fix and the GDOP is better than in the time-difference mode. Use of integrated Transit and Loran-C receivers, with the Loran-C providing the velocity information necessary to provide a satellite fix in moving vehicles, has resulted in an accuracy of 10 meters [6]. However, due to the long elapsed time between satellite fixes, continuous operation is not possible.

Position accuracy can be improved with a differential mode of operation, by transmitting differential corrections to user receivers from several Loran-C monitoring stations located along the seaway at appropriate intervals. An experimental study conducted by the U.S. Department of Transportation [8], on the use of differential Loran-C in navigating the St. Lawrence Seaway, concluded that the North East Loran-C chain fails to meet the cross track accuracy requirements applicable to one-way traffic, for a majority of Seaway reaches, even if a perfect differential correction technique is used. The measurements, after the introduction of error-free differential corrections, revealed a short-period component with variations in the mean one order of magnitude greater than the standard deviation of the mean for a normal distribution. In addition to the short term drift (less than 5 minutes), a longer-period component (few days) with much larger mean deviation was observed. It was not determined whether this is due to the receiver or localized propagation or multipath effects.

A system operating in the differential mode will neccessarily be more complex since highly reliable dedicated communication links are required. This introduces additional problems of licencing and maintenance of several shore-based differential stations with the related additional expense.

3.1.4 NAVSTAR: GLOBAL POSITIONING SYSTEM (GPS)

In the NAVSTAR GPS system, the user equipment roughly estimates system time and performs "pseudo-range" measurement to at least three geometrically dispersed GPS satellites, to derive a position fix [9]. In order to correct for the error between the actual GPS time and the estimated time, a pseudo-range measurement to a fourth satellite is used. All satellites use a 10.23 MHz atomic frequency standard and transmit on two frequencies L_1 at 1575.42 MHz and L_2 at 1227.6 MHz, which are coherently derived. The L_1 signal is modulated with two pseudo-random noise codes in phase quadrature, called the Precise(P) and the Coarse/Acquisition (C/A) codes. The L_1 and L_2 signals are also modulated with a navigation data bit stream at 50 bits/second. Only the C/A code is available for civil use. It is transmitted at 1.023 Mbits/sec, repeating each millisecond.

The pseudo-range measurements are affected by refraction from ionospheric and atmospheric effects, which cause differences in the path length. The overall delay is approximately inversely proportional to the square of the transmitted frequency. This relationship is used for a first-order correction of the measured values. In a more sophisticated user instrument, the pseudo-range to each satellite is measured at both frequencies L_1 and L_2 and the difference between the two measured values is used to determine the propagation delay error [9]. During normal operation, the L_2 signal is modulated only by the P-code, which is available only for military use.

As in the case of Loran-C, there is also the additional GDOP factor to be considered. With the proposed 18-satellite baseline plus three on-orbit spares, there will be short gaps in coverage at the mid and high latitudes due to geometrical effects. In order to achieve low GDOP factors, it becomes necessary to combine measurements from all satellites in view above an arbitrarily selected satellite view angle. This combining must be repeated for both frequencies, since corrections must be applied for ionospheric propagation delays.

As a result of tests using GPS receivers with the seven (Block I) satellites which are currently in orbit, accuracies measured were in tens of metres rather than the predicted 100 m. For security reasons, a decision has been made to intentionally degrade the accuracy available with the C/A code to 200 m (CEP) or approximately 500 m at 95-percent confidence level, when GPS becomes operational [9].

Differential operation is used to remove bias errors by comparing the signals at one receiver to those obtained at a second stationary receiver, whose location is precisely known. The output of the second receiver is transmitted to the first receiver through a communication channel. Tests conducted on the ISTAC SERIES system has shown that a differential processing of two receivers 100 kms apart gives a relative position accuracy of 1 metre, with data averaging [10]. The factors which affect the accuracy of differential correction include the following [11]:

(1) Geometric decorrelation - ephemeris errors are not completely cancelled; this error is proportional to the user-station separation.

(2) Ionosphere/troposphere - signal paths to the two receivers traverse atmospheric volumes that produce different delays.

(3) Earth curvature - a satellite visible to the user may not be visible to the differential station.

(4) Blockage and multipath - satellites visible to the differential station may not be visible to the user due to blockage from terrain, buildings, trees and other structures. The signals may also be affected by strong reflections from structures causing localized multipath effects.

Figure 3.2 shows the pseudo-range errors for a marine/land receiver and their dependence on the satellite elevation angle. The achievable accuracies with a differential operation are indicated in Table 3.2 where the marine receiver uses a two-dimensional solution and the aircraft receiver uses a three-dimensional navigational solution [11]. The differential station would be able to use a lower satellite view angle and have a better signal-to-noise ratio, since it would be located at a favourable location and have a better antenna characteristic. Blockage due to buildings and other structures can be reduced by suitable siting and elevating the antenna. Multipath can cause serious problems if siting favours strong reflections.

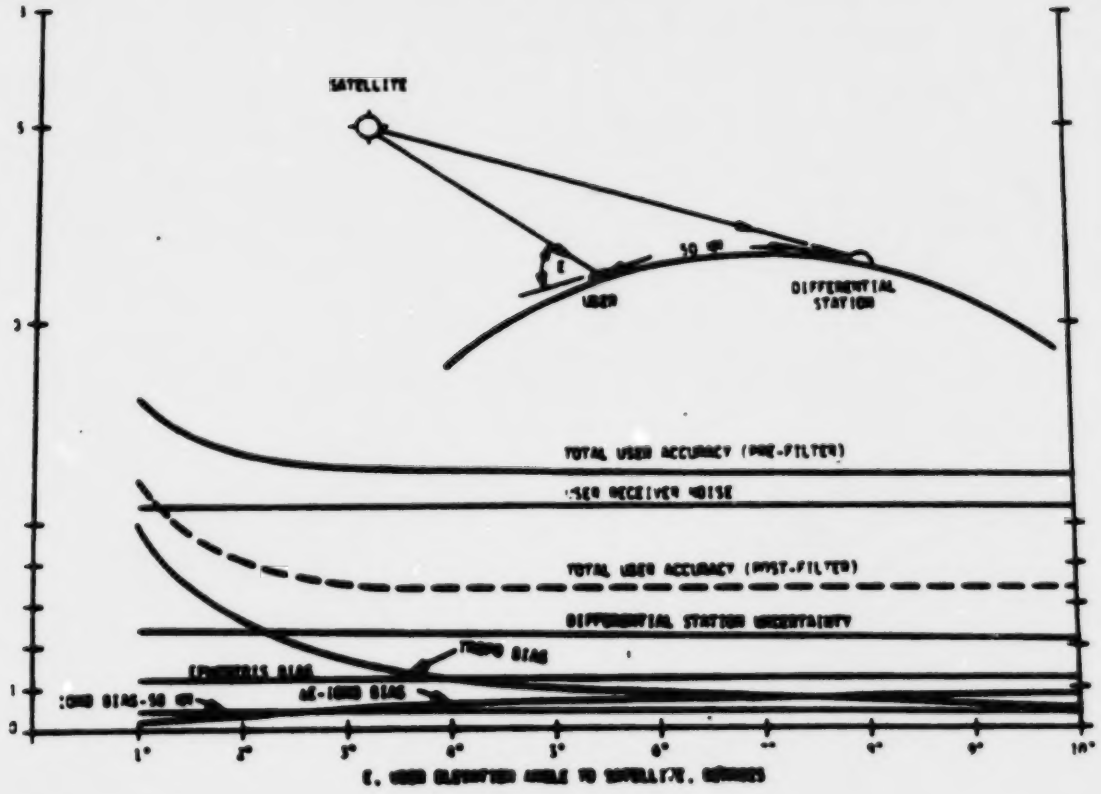


Figure 3.2 Differential Pseudorange Errors for a Marine/land Receiver with 50 km User-reference Separation [11]

Table 3.2 Achievable Accuracies with Differential Operation (2drms) [11]

Navigation solution algorithm	Satellite selection algorithm	Mask angle	Median HDOP	Accuracy meters
(marine)	Best-set-of-three	5°	1.43	9.7
		10°	1.52	10.3
	All-in-view	5°	1.08	7.3
		10°	1.20	8.2
(airborne)	Best-set-of-four	5°.	1.50	12.0
		10°	1.60	12.8
	All-in-view	5°	1.13	9.1
		10°	1.32	10.6

Note: This table does not consider temporal variations. The accuracies cited would thus be representative of differential systems with a high update rate.

From the above considerations, the applicability of differential GPS to Seaway navigation relies on the following factors:

(1) Differential stations should be set up at intervals of about 50 to 200 km [10] at suitable sites and corrections transmitted to the user receivers continuously. Temporal variations will be minimized by using a high data rate.

(2) Blockage and multipath effects are required to be minimized by suitable siting of the differential stations and by maximizing the height of the shipboard receiver antennas.

(3) Sufficient satellite coverage must be available with no outages, i.e.: all the 18 satellites (with 3 spares) are required to be operational, providing continuous service at the specified accuracy level.

Since the full operational capability of the GPS will be achieved only around 1990, its performance on the Seaway cannot be realistically evaluated before then. It may not be possible to use this system in certain reaches, where blockage might be a problem.

In the differential system considered above, the pseudo-range corrections were assumed to be transmitted to the user. More recently, other differential techniques such as the pseudo-satellite differential GPS and differential time GPS have been proposed. In the pseudo-satellite or pseudolite system [12] the transmitter of the differential station monitor is similar to that used aboard the satellites themselves. This pseudo-satellite transmits corrections determined by its own monitor as well as a conventional GPS navigation signal. This mode of operation may be useful in areas affected by blockage or poor satellite geometry.

The differential time GPS [13] uses an incremental model for the navigation solution. The incremental changes in XYZ position and time (ΔX)

and incremental changes in the ranges to the satellite (ΔR) are related by the equation:

$$\Delta R = G * \Delta X + N$$

where G is the geometry matrix containing the directional cosines and N represents the noise in the measurement. If the wavefronts from each satellite are assumed to be linear in the area of measurement, then the differences in ranges at the two sites (ΔR) are proportional to the differences in the times of arrivals of the signals at the two sites (ΔT). The user's position can be estimated, relative to a differential station monitor, using a least squares estimate. Differential time GPS avoids most of the satellite fix computation, since all differential schemes require the times of arrival of the signals from the satellites to be measured at the monitor as well as the stations. It is thus a local or short-range relative navigation system that uses long-range emissions as opposed to a long-range navigation system that uses local corrections. Since the GPS signal repeats every millisecond, the ambiguity lane width is 300 km and ambiguity is not a problem within a 150 km radius of the monitor.

Due to the above considerations, differential GPS operation may become viable in the future, for precise relative positioning. It is likely that ambiguities associated with differential GPS will be resolved in the near future, as the system becomes more popular.

The GPS system is not considered further in the present study, because of the lack of availability of a fully operational system at present and insufficient knowledge about future possibilities. As mentioned previously, differential operation involves highly reliable dedicated communication channels and somewhat complex shore-based stations, involving licencing problems and added system cost.

3.2 SHORT-RANGE SYSTEMS

The systems discussed in Section 3.1 were global systems having a long operating range. Systems which are used for rather localized applications, operating at short range, include precision radionavigation and positioning systems, radar systems, radio direction finding systems,

laser systems and underwater acoustic systems. These systems are used in precise relative local positioning applications such as aircraft landing, ship navigation in restricted waters, relative navigation of ships or aircraft moving in a formation, tactical battlefield management, positioning of remotely operated vehicles (ROVs), hydrographic and oceanographic surveys etc.

Of the above systems, laser and acoustic systems are not useful for Seaway navigation because the laser approach is not an all weather system and acoustic systems require installation of sensors or transponders over the bed of the channel, which may be damaged due to scouring by ice or sometimes even the ships themselves. Therefore these approaches are not considered further.

3.2.1 SHORT-RANGE RADIONAVIGATION AND POSITIONING SYSTEMS

Precise local radionavigation and positioning systems can be classified into those that operate on the principle of pulse matching and those that use phase comparison. The pulse matching type of systems normally are precise ranging systems or Distance Measuring Equipment (DME), which include microwave systems such as Precision DME (DME/P) used for civil aviation, Motorola Mini Ranger, Racal Micro-fix, Del Norte Trisponder as well as UHF systems such as Sercel Syledis, Maxiran or Del Norte UHF Trisponder. The phase comparison systems mostly operate at medium frequency (MF) and include systems such as ONI Microphase, Cubic Western Argo DM54, Racal Hyper-fix and Teledyne Hastings Raydist.

3.2.1.1 Ranging Systems

Precision DME is used in aircraft landing systems to provide the distance information by measuring the total round-trip time between interrogations from an airborne transmitter and replies from a ground transponder. The DME/P system, which is an integral part of the Microwave Landing System (MLS) for aircraft approach and landing, must be capable of providing accurate (12 m) range information in a potentially severe multipath environment [14]. Since multipath perturbations occur

later in time than the desired signal, they are minimized by thresholding the received pulse at a low level (about 17 dB below the pulse peak) on the leading edge of a fast rise time pulse. A time-of-arrival (TOA) technique such as the Delay, Attenuate and Compare (DAC) is used which compares a delayed version of the pulse to an attenuated version of the same pulse and declares a pulse arrival when the delayed signal exceeds the attenuated signal. With a delay of 100 nsec and an attenuation of -5 to -6 dB, a nominal threshold level of 15 or 18 dB below the pulse peak is obtained [14]. Another problem in DME systems is the garble due to interference from other DME equipment operating in the surrounding environment. This must be reduced by channel assignment, limiting the number of users, signal identification and validation etc. DME/P, as specified by the international Standards and Recommended Practices (SARPs) for civil aviation use, has a path following error (PFE) of 30 m for standard 1, 12 m for standard 2 and 85 m for Initial Approach (IA) mode [14].

Other ranging systems using the pulse-matching technique include microwave systems such as the Motorola Mini Ranger, Del Norte Trisponder and Racal Microfix and UHF systems such as Sercel Syledis, Thomposon Trident, Del Norte UHF Trisponder etc. A master station located on the user's vehicle interrogates a number of remote transponder stations in turn and, by measuring the time interval between the transmitted interrogating pulse and the received reply, the range of each remote station is determined. A typical accuracy of ±1 m is achieved by these systems under good conditions of geometry. Inter-station interference is avoided by using a unique code system or multiple frequencies, with each remote transponder unit preset to recognize its own unique station code.

General operational problems related to ranging systems include the following:

(a) Multipath effects;

(b) Propagation and weather effects;

(c) Geometrical dilution of precision (GDOP);

(d) Interference with other systems; and,

(e) Licencing.

Multipath effects in microwave systems are minimized by employing circular polarization techniques to eliminate nulls and reject horizontal reflections. Propagation errors are reduced by using short-range line of sight stations. With 3 or 4 stations, a good geometry is obtained and the GDOP is minimized. A positioning accuracy of ±3 metres is claimed realizable with a reasonable GDOP. The transmit/receive (T/R) units can be fitted with a sector antenna in place of an omni-directional antenna to avoid interference with other nearby stations. If the operating frequency is in the microwave band, quite removed from the frequencies used by other regional services, it is usually not difficult to obtain licencing for operation.

The drawback of a microwave or UHF ranging system includes the capital and operational costs for a large network of shore-based T/R units, however the technique provides the required performance and is considered further in Section 5.

3.2.1.2 Phase Comparison Systems

Positioning systems using phase comparison are normally medium frequency (MF) systems, depending on the ground wave mode of propagation. The difference in the phase of signals, received from a pair of transmitting stations, defines a line of position (LOP). A position fix is obtained by the intersection of two or more LOPs. The inherent ambiguity of one wavelength in phase measurement is continuously monitored by lane counting and corrected in the receiver. The transmitting stations operate on a time-shared basis and have a typical operating range of about 250 km.

In the hyperbolic mode of operation, up to about six transmitting stations are located on the shore and hyperbolic patterns are generated across pairs of selected stations. The station sites are selected so as to provide a favourable geometry ensuring that the patterns intersect to provide a useable hyperbolic lattice. A set of contours of constant root-mean-square (RMS) error is derived from the geometry, as shown in Figure 3.3 for a typical set-up, indicating 5 m and 10 m error contours, assuming a standard deviation of 0.01 of a lane [15]. Since the error

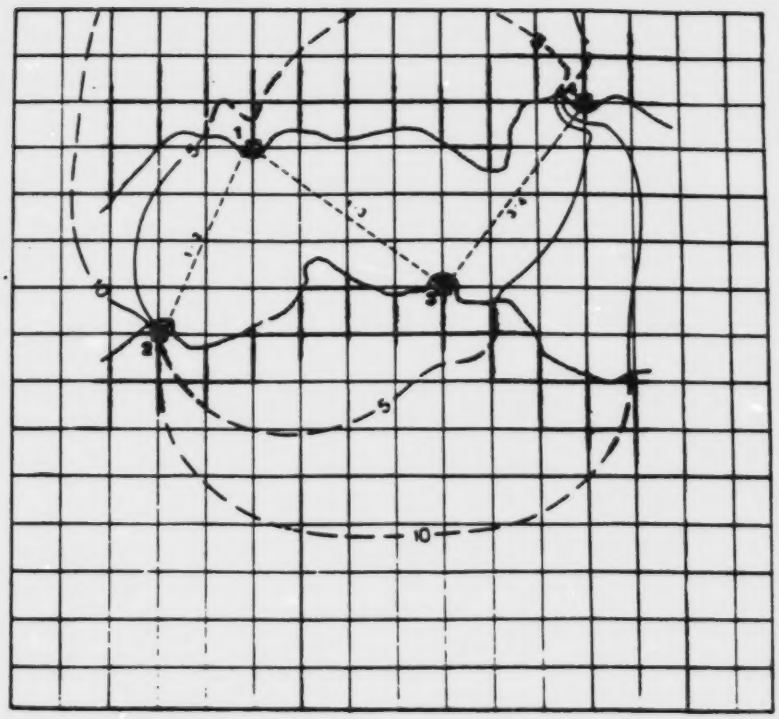


Figure 3.3 RMS Error Contours for the Hyperbolic Mode of Operation

contours are to a large extent independent of scale up to a certain limit, the baseline lengths can be increased without changing the geometry, thereby enlarging the area of coverage. The maximum possible baseline length is chosen, dictated by signal strength limitations and the increase of standard deviation with range. A positioning accuracy of about 5 m may be obtained with a system in the hyperbolic mode, using four or five transmitting stations covering a range of about 300 km.

As in the case of the ranging systems, the operational problems with the MF phase comparison systems include multipath, propagation and weather effects, GDOP, interference with other transmissions and licencing. These effects, except multipath, are much more severe, than in microwave ranging systems, because of the larger range of operation and wider area of coverage. It may be quite difficult to obtain necessary licencing for transmitting in the MF band. Multipath and propagation effects can cause errors in measurement due to signal fading. Since the operating environment in the Seaway is generally favourable to multipath reflections, and the long range of operation is likely to enhance the propagation effects and interference, and with the additional problem of licencing, a phase comparison system is considered marginally useable for Seaway Navigation. System redundancy is also poor, because failure of one of the four stations causes the accuracy of the entire system to degrade severely.

3.2.2 RADAR POSITIONING SYSTEMS

A radar system such as the ship's radar measures both range as well as the bearing in azimuth to targets. Radar range data are inherently more accurate than the angular data, beyond a certain range. The range error σ_r remains essentially constant with increasing range, whereas component due to angular error σ_θ, increases with range as $R\sigma_\theta$. If σ_θ is equal to 1 degree, and σ_r = 3 metres, at a range R equal to 171.9 m, the value of σ_r equals $R\sigma_\theta$. When $R > \sigma_r/\sigma_\theta$, the positioning error starts increasing rapidly. In such instances, radar trilateration systems based on range measurement are normally used.

Some possible configurations for radar positioning systems are as follows:

(a) Trilateration using shore-based radars;

(b) Interferometry using shore-based radars;

(c) Range measurement using ship-based radar;

(d) Image correlation using the ship's radar image.

The options involving shore-based radars may be assumed to be long-range measurements in order to reduce the number of shore-based installations required. The measurements involving the ship's radar can be performed at short-range using several shore-based reflectors or transponders or short-range imagery. Use of sophisticated radar systems, such as an interferometer radar on the ship, is excluded from consideration because of practical cost limitations.

3.2.2.1 Trilateration Using Shore-Based Radars

A shore-based chain of radars may be used for detecting targets located on each ship, using both range and angle measurements. With two radar beams intersecting at a right angle, as shown in Figure 3.4a, the error in target position may be described by a circle of probable error, whose radius is equal to the error in range measurement (σ_r). For other cases, this error is given as an ellipse whose major axis is given by [16]:

$$\sigma_n = \sigma_r C_e (GDOP)$$

where C_e is the correlation between the two range errors (equal to $\sqrt{2}$ for radars which are separated enough to have no correlation in their errors), and GDOP is the geometrical dilution of precision, which depends upon the angle at which the beams intersect (2α).

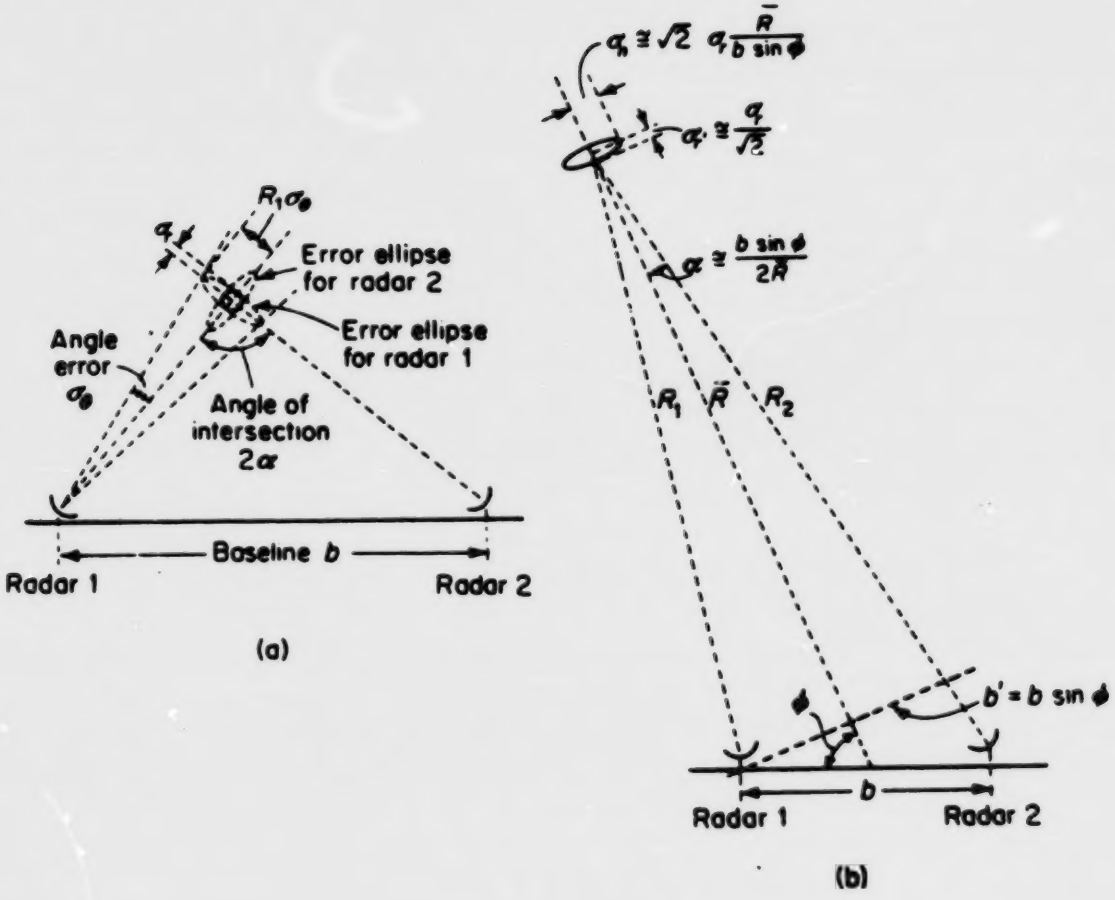


Figure 3.4 Radar Range Trilateration [16]
(a) Radar Beams Intersecting at Right Angle
(b) Angle of Intersection less than 90°

The two components of position error, as shown in Figure 3.4 are:

$$\sigma_r' = \frac{C_e' \sigma_r}{2 \cos \alpha} \quad \text{and} \quad \sigma_n = \frac{C_e \sigma_r}{2 \sin \alpha}$$

When $\alpha = 45°$, $\sigma_r' = \sigma_n = \sigma_r$. For small α, $\sigma_n \simeq \frac{C_e \sigma_r}{2\alpha} = \frac{C_e \sigma_r \bar{R}}{b \sin \theta}$ from Figure 3.4b. The error σ_n increases for small values for ϕ and for $b << R$, due to poor geometry. The σ_n error can be considered as an equivalent angular error of

$$\sigma_\theta' = \frac{\sigma_n}{\bar{R}} = \frac{C_e \sigma_r}{b \sin \phi}$$

For two radars with σ_r equal to 3 m and situated 50 km apart, if $\bar{R}$ is equal to 50 km, then $\sigma_n = \sigma_\theta' \bar{R} \simeq \frac{\sqrt{2} \times 3}{\sin \phi} = 7.5$ m for $\phi = 34.45°$. If ϕ is to be maintained at values higher than about 35 degrees, it becomes necessary to locate the radars farther away from the channel, or increase the number of radars on the shore. Long range radars would also suffer from blockage and multipath effects. In order to avoid blockage due to structures, terrain and vegetation, either each radar must be located at a considerable height, or more radars have to be used. Multipath, not only from the ground but from other vertical structures, can cause severe problems. The complexity of the radar installations and the need to man each radar site for operations significantly increase the complexity and cost of such a system. In addition, a dedicated communication data link will be required to transmit the target information to the ships. Due to these severe disadvantages and limitations a shore-based radar trilateration system is not recommended for Seaway navigation.

3.2.2.2 Shore-Based Interferometer Radar

The interferometer radar system is operated with CW signals transmitted by a cooperative transponder. The range is measured by phase comparison of modulation frequencies superimposed on the CW carrier. By comparing the RF carrier phase, angular measurements are made. Figure 3.5 shows the geometry of a simple interferometer system [16].

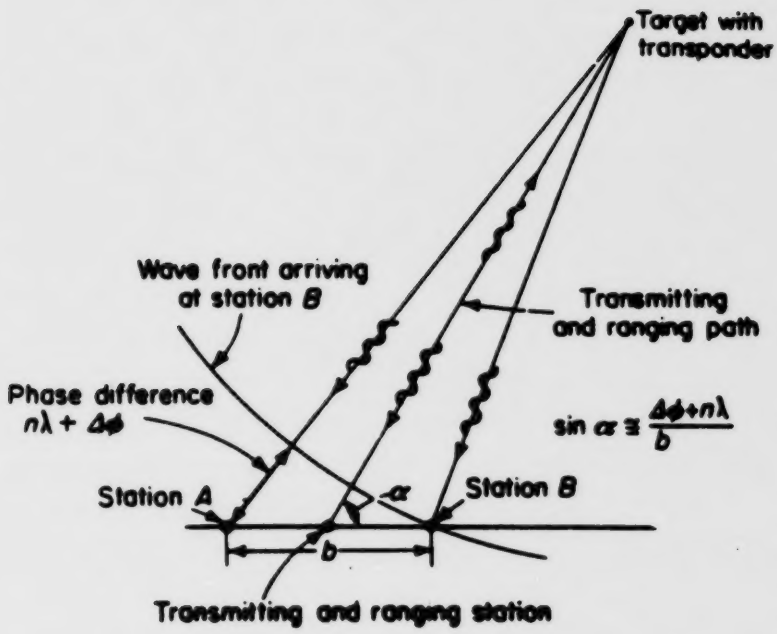


Figure 3.5 Interferometer System Geometry [16]

The two radar stations A and B are located at the two ends of a long baseline. The pattern produced by two antenna elements located at A and B will have a series of lobes separated by an angle

$$\Delta\alpha = \frac{\lambda}{b \sin \alpha}$$

where λ is the wavelength of operation, b is the baseline length and α is the angle between the baseline and the direction of the target. The theoretical precision of the interferometer is given by [16]

$$\sigma_\alpha = \frac{\lambda}{\pi b \sin \alpha \sqrt{R}} = \frac{\Delta\alpha}{\pi\sqrt{R}}$$

Where R represents the energy ratio of the signal measured over the total observation time. For a baseline length of 10 km, frequency of operation at 5 GHz, α equal to 3° and energy ratio of 10, the theoretical precision in the angular measurement is about 12 microradians.

The interferometer radar system is normally used in an X or L configuration, in order to measure two orthogonal angles. The variation in length and orientation of the baseline are usually major problems with interferometry. The electrical length of the baseline must be maintained to the required accuracy using water-cooled waveguides, filled with dry air at a controlled pressure. If the radar antennas are of the rotating type, the distance between their phase centres must be carefully controlled.

Multipath and atmospheric refraction are other major problem sources. Multipath effect can be kept low by using directional antennas with low sidelobes. However, if the range of operation is large, localized multipath effects cannot be controlled. Low frequency components of refractivity change cause severe limitations on interferometer systems. In order to resolve ambiguities in phase difference data and identification of the

proper lobe in the pattern, the system is required to be quite complex. In addition to a large number of radars, it is also necessary to maintain dedicated communication links to transfer the data in "real-time" to the ship. Due to the complexity in operation and operational problems, a shore-based radar interferometer is not a good choice for Seaway navigation.

3.2.2.3 Range Measurement using Ship-Based Radar

Since all ships are fitted with marine radars, any navigation system that utilizes the output of these radars can be quite cost effective. A radar discriminates targets from noise or clutter by using one of the following parameters:

(a) Amplitude;

(b) Frequency;

(c) Phase; and

(d) Polarization

In the case of the marine radar, amplitude thresholding is used for target detection. The amplitude of the return from a target at a particular range is proportional to the reflectivity and size of the target, for a given set of radar parameters. Reflections from scatterers such as waves, terrain or structures introduce a distributed clutter background against which targets must be detected. This clutter is sometimes enhanced by environmental effects, multipath etc. Detection of targets against background clutter can be improved by using additional discriminating factors such as frequency, phase or polarization. A system using phase as a discriminant requires a coherent radar on the ship. Since marine radars are generally non-coherent in operation, and converting them into coherent radars is quite expensive, using phase for target discrimination is ruled out. Use of polarization and frequency as discriminants is studied in the following sections.

The problems associated with polarization discrimination are:

(a) Sidelobe performance for targets and clutter;

- Cross polarized returns from clutter sources;
- Antenna feedthrough and coupling;

(b) Time jitter in the radar transmitter/receiver;

(c) Transmitter pulse shape;

(d) Interference from other shipborne radars;

(e) Blockage due to other ships or other structures on the ship;

(f) Target identification;

(g) Ship's rolling, and

(h) Weather effects.

The sidelobe attenuation of a typical shipborne antenna is about 24 dB one-way. Clutter as well as targets in the near range can get into the receiver through the sidelobes. For example, a two-way sidelobe attenuation of 40 dB would be equivalent to a factor of 10 in range, since the radar return is proportional to the fourth power of range. If the radar is set up to detect targets at a maximum range of 10 km, then the receiver output will contain targets at 1 km range, detected through the sidelobes. This problem is reduced by using a sensitivity-time-control(STC) circuit, which applies a range dependent attenuation to the receiver output. However, since the dynamic range of the radar receiver is limited, the output for nearby targets and clutter reaches the saturation level. A dynamic range of 80 dB gives a range ratio of 100. For example, with an operating range of 10 km, the saturation level is reached at 100 m.

3.2.2.3.1 Polarization Discrimination

The design of a passive radar reflector that converts the polarization of an incident radar wave from horizontal to vertical and its use for Seaway navigation has been studied in detail at McMaster University [17,18,19]. The cross polarized return from clutter sources is considered to be typically 10 dB lower than the like-polarized return [18]. By enhancing the passive radar reflector return for cross polarization, additional discrimination can be obtained. To receive the cross polarized component it is necessary to modify the ship's antenna by adding an extra receive array for vertical polarization, as well as a control unit to switch between the horizontally polarized antenna for transmit and the vertically polarized antenna for receive operations.

Spatial diversity has been proposed to solve problems related to multipath. Experiments have been conducted at the Hamilton harbour on a static radar platform using static reflectors and comparing their returns against background clutter. Comparing the like and cross polarization returns from the twisted grid reflector, an enhancement of about 18 to 20 dB in discrimination was observed at X-band, with an optimum reflector to grid separation, as shown in Table 3.3.

Cross-polarized returns are produced by man-made structures, vegetation and terrain. Figure 3.6 illustrates the depolarized return for a radar using horizontal polarization for transmission [20]. The cross-polarized component is down about 10 dB from the like-polarized return. In order to obtain a signal-to-clutter ratio of 10 dB for target discrimination, it is required to build reflectors which have a radar cross section equivalent to the strongest targets in the coverage zone. It is possible to significantly reduce and possibly eliminate the effect of depolarizing clutter with a tracking system, since strong clutter sources might have a tendency to fluctuate as a function of the look angle in azimuth. By tracking targets continuously and checking their geometry, the false targets may be suppressed or avoided. If distributed clutter is detected close to a target reflector, the tracking algorithm can omit this target from consideration.

Table 3.3 Reflector Performance

Incidence Angle	X/L (dB)	R/X (dB)	Conversion Efficiency (%)
Normal	18 - 20	1	79
±10° Azimuth	10	2 - 3	50
±10° Elevation	8 - 10	4	40

R: Like polarization return for reflector without grid
L: Like polarization return for reflector with twisted grid
X: Cross polarization return for reflector with twisted grid

Grid-reflector separation: 1.9 to 2 cm
Frequency: 9.3 to 9.5 GHz
Wire diameter: 0.045 mm
Wire spacing: 5.5 mm

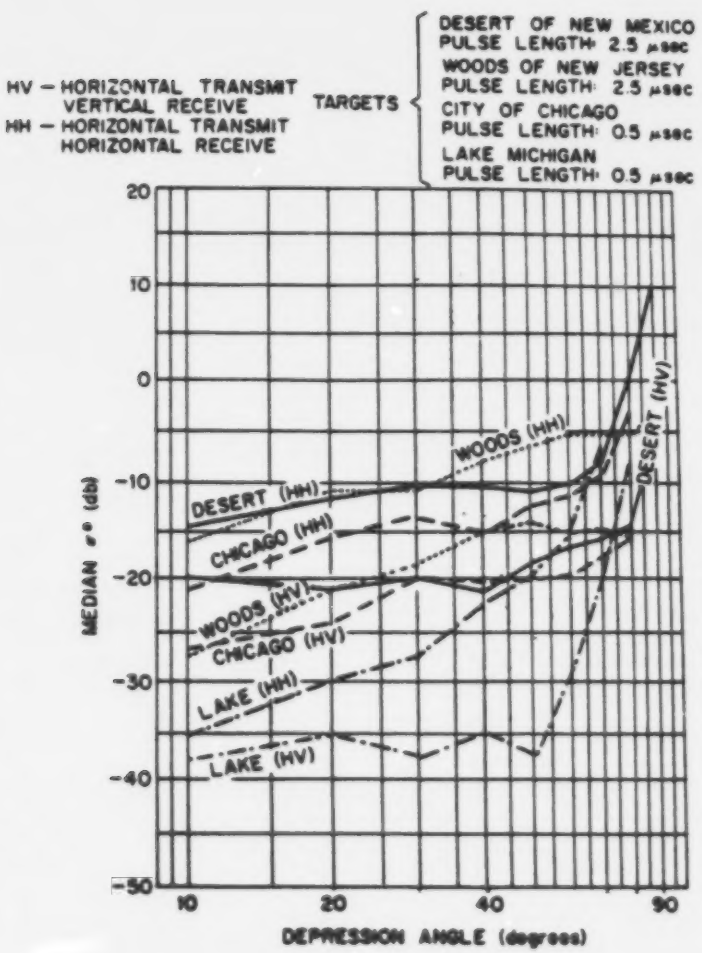


Figure 3.6 Example of the Depolarization of a Radar Return Naval Research Laboratory Data [20]

Cross coupling of energy, from the horizontally polarized antenna and feed system, to the vertically polarized antenna and feed can enhance cross polarized clutter and produce false targets. In McMaster University trials, some of the strong clutter seen at the Dofasco reflector site was attributed to antenna feedthrough. This effect may be reduced by using proper shielding between feed cables and using a commutating switch with a high isolation between the two switched channels. A radar antenna is currently being developed at the University of Manitoba with an isolation design objective of 45 dB.

Jitter in the timing signals and pulse shape are factors directly related to the performance of the marine radar. The characteristics of a typical civilian marine radar are listed in Table 3.4 [21]. Range is measured in a radar by the measurement of time delay $T_R = 2R/C$, where R is the range and C is the velocity of light. With a pulsed waveform, the time at which the leading edge of the pulse crosses a defined threshold is measured, as shown in Figure 3.7 [22]. The slope of the leading edge of the pulse is A/t_r, where A is the pulse amplitude and t_r is the rise time. If the signal-to-noise ratio is high, the slope of the pulse corrupted by noise, given by $n(t)/\Delta T_R$ from figure, is nearly equal to A/t_r, where n(t) is the noise voltage and ΔT_R is the resulting time-delay error.

$$\Delta T_R = \frac{n(t)}{A/t_r}$$

$$\left[\overline{(\Delta T_R)^2}\right]^{1/2} = \delta T_R = \frac{t_r}{(A^2/\overline{n^2})^{1/2}} = \frac{t_r}{(2S/N)^{1/2}}$$

Table 3.4 Parameters of Typical Non-military Marine Radar [21]

Frequency band:
9,330 to 9,500 MHz

Polarization:
Horizontal (vertical in some sets)
Alternative circular polarization sometimes available

Antenna beamwidths:
Horizontal: 0.6 to 2.4°, depending on aperture width
Vertical: 15 to 25°

Antenna sidelobes:
Within ±10° of main beam -23 dB to -30 dB
Outside ±10° of main beam -30 dB or better

Antenna rpm:
Between 12 and 25 (most sets 20). One set 80.

Transmitter peak power:
Between 3 and 75 kW (usually 10 kW)

Transmitter pulse repetition rate, pps:
Between 6,000 and 500. Most sets have two or three rates available, tied to different pulse lengths and display range scales.

Transmitter pulse length:
Between 0.05 and 1.2 μsec
Most sets have two or more pulse lengths, tied to different range scales and receiver bandwidths.

Receiver bandwidths:
Between 2.5 and 30 MHz. Many sets have two or more bandwidths tied to different pulse lengths and range scales.

Receiver noise
Between 9.5 and 14 dB.

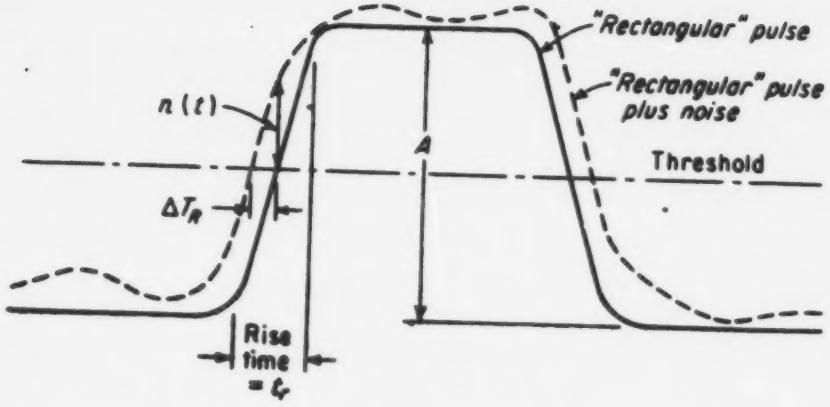


Figure 3.7 Measurement of time delay using the leading (or trailing) edge of the pulse. Solid curve represents echo pulse uncorrupted by noise. Dashed curve represents the effect of noise [22]

where the video signal-to-noise power ratio $A^2/\overline{n^2}$ is equal to twice the IF signal-to-noise power ratio (S/N), assuming a linear detector law. If the video pulse rise time is limited by the IF amplifier bandwidth B, then $t_r \approx 1/B$. For a rise time of 20 nsec and S/N equal to 10 dB, the time-delay error is 4.5 nsec or 0.68 m. A second component of the time-delay error is caused by jitter in the timing signals. Assuming a 10 nsec jitter, the total error is 14.5 nsec, which is equal to a range error of 2.2 m. The effect of jitter will be reduced by pulse-to-pulse averaging of the time-delay measurement. The sampling rate of a suitable video digitizer is assumed to be 50 MHz (i.e. over twice the bandwidth B); therefore the range resolution will be limited to 3 metres.

Interference from other radars operating at the same frequency can be suppressed by using pulse-to-pulse correlation. This is done by storing the digitized range data for one pulse repetition period and comparing them with the corresponding range data for the following pulse. Only those returns which appear in both consecutive periods are passed on as correlated video.

Blockage due to other ships while crossing can be overcome by using extra reflectors (The same holds true for blockage caused by structures on the ship such as masts); as an alternative, one of the ships might be halted to allow the other to pass.

Since the returns from each of the reflectors is identical, the reflectors have to be identified by the tracking system. From the radar range and bearing information, the tracker is required to anticipate the expected relative positions of each of the individual reflectors. The tracker must be initialized at the beginning of a run, when the ship is moored at a calibrated location.

Since the targets are located at accurately surveyed sites, any false targets picked up by the system can be easily identified and rejected. Information regarding clutter in the vicinity of a target may also be stored in the system, along with target information, for easy identification of false targets. It is also possible to distinguish point targets from distributed clutter, by looking at range and azimuth bins adjacent to the target's location.

The effect of pitching or rolling of the ship can change the direction of polarization. This effect is likely to be very small, since the maximum roll is limited to about two degrees. Weather effects such as icing are not considered to be major problems with the reflectors since they are positioned vertically. Cross polarization helps in the rejection of rain echoes. A rain clutter cancellation of up to 40 dB can be achieved with cross polarization.

With the above considerations, the polarization discrimination scheme using the ship's radar is a possible solution and is studied in detail in a later section.

3.2.2.3.2 Frequency Discrimination

By modifying the ship's radar to receive a frequency slightly different from the transmitted frequency and using transponders which reply at the offset frequency, a frequency discriminating scheme can be implemented. Transponders are available which can transmit either an on-frequency signal or a signal whose frequency is different from that of the signal received by the transponder. The off-frequency transponder can be detected against background clutter by detuning the radar receiver to receive only the offset frequency. The transponders can also be set up to transmit independent codes for identification purposes.

The frequency discrimination scheme is very similar to polarization discrimination in implementation. The shipborne radar is used to obtain the ranges to three or more targets and the position of the ship is obtained by inverse triangulation. The azimuth angle information from the radar is used to check the approximate direction of the target and its identity. Range information is used mainly because of its better accuracy compared to the angle information obtained with a 1 degree wide beam. With a range accuracy of about 3 metres, and a reasonable geometrical dilution of precision, the positional accuracy of ±7.5 m can be met.

The problems encountered with frequency discrimination are similar to those associated with polarization discrimination. The transponders may be triggered through the sidelobes of the ship's radar, when they are in near range. This will produce a circle of constant range on the ship's radar display instead of showing up as a point target. It is necessary to use a sidelobe suppression (SLS) technique to avoid this problem. The ship's antenna does not need modification nor is there a problem of feedthrough or coupling. As before, spatial diversity must be used to reduce multipath effects by suitable design of the transponder antenna. The transponders can be powered by regular a.c. mains whenever possible, with provisions for a back up battery system. In remote areas, battery packs, thermoelectric generators, solar panels, etc, will be required. The transponder stations required periodic maintenance, contributing to the total system operational costs.

The details of implementation of the frequency discrimination scheme are discussed in a later section.

3.2.2.4 Image Correlation Using Ship-Based Radar

On-line computer processing of radar images has been recently proposed as a means for navigation in coastal regions [23]. Two types of operation have been considered. The first is to overlay radar images of land clutter on an electronic chart (a digital map of the surrounding area), and find the position of the ship by comparison of the two images. The second method is to compare the ship's radar image with other radar images stored in the computer for a nearby location. Positional accuracies of the order of 100 m has been obtained with the first method. A position-keeping accuracy of better than 10 m has been obtained with the second method.

Figure 3.8 gives the details of the equipment used in an experiment conducted by McGill University [23]. With a radar PRF of 300 Hz, a total of 3000 radials were acquired per rotation, each containing 1024 range cells of length 25 m, for a total range of 25.6 km. The radar trigger, log video and azimuth information were fed to the digitizer. The log video for each range cell was converted to a 6 bit code giving an intensity resolution of 64 levels. The digitized chart overlays used in the first method provided, in general, 100 m resolution.

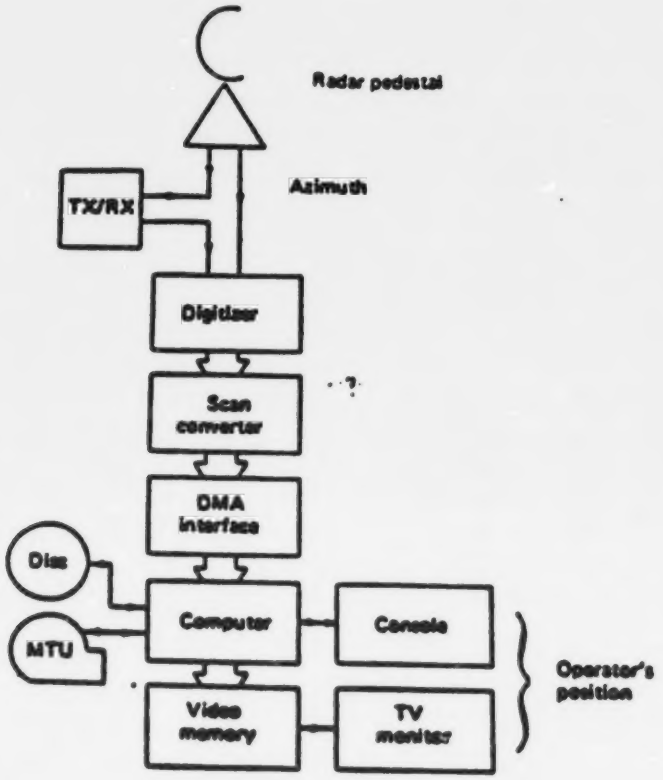


Fig. 1. System hardware

TABLE 1. RADAR CHARACTERISTICS

Frequency	3880 MHz
Pulse duration	250 ns
Peak power output	1 MW
P.r.f.	300 Hz
Antenna	10 m parabolic reflector
Beamwidth	0·8° azimuth and elevation to 3 dB points
STC	None
R.p.m.	6
Range bin length	25 m
Digitizing rate	6 MHz
Digitized intensity levels	64 (6 bits)
Bandpass	8 MHz
Sensitivity	10 m^2 target is 68 dB above noise at 12 km range

Figure 3.8 Image Correlation System [23]

The pattern-recognition technique uses a cross-correlation algorithm to find the best match between the current radar image and the map overlay or the radar image stored in the computer for the specific area. The cross-correlation coefficient is computed for all possible displacements until its maximum value C_{max} is identified. The translation necessary to obtain C_{max} gives the vector defining the displacement of the ship with respect to the reference location. Several reference locations along the channel course line can be selected as optimal and a radar image obtained at these locations and stored in, for example, a laser disc memory. If necessary, this data base can be repeated for different seasons of the year to take into account seasonal changes of the shore line and land clutter. The final positioning to a fraction of a grid length is accomplished by finding the centre of gravity of nine correlation coefficients centred on the lag of C_{max}.

Since processing of the radar image is carried out in a Cartesian grid, a scan converter is used to transform the polar radar data into Cartesian co-ordinates. When the Cartesian resolution selected is finer than the resolution of the polar data, 'holes' or pixels with no data appear at far range in the converted image. These 'holes' are filled by interpolation or by repeating radials during the polar/Cartesian conversion.

Problems associated with the image correlation scheme include viewing angle effects and weather clutter. The radar image of land clutter varies with the viewing aspect because of the three-dimensional nature of the terrain. This effect can only be minimized by increasing the number of reference points. Clutter due to localized weather effects such as rain can be minimized by processing sectors of the image for good fit and excluding those regions that give poor correlation. Interference from radars of other ships in the vicinity must be removed by pulse-to-pulse correlation. Blockage problems can be minimized by sector processing, as in the case of rain clutter.

The system has a built in measure of performance in the value of the correlation coefficient. If this value goes too low, a warning flag may be set to indicate the degradation of performance of the system.

The main advantage of the image correlation scheme is that it does not require any modifications to the ship's radar system. It can be easily interfaced to any radar, since it operates only on the video output of the radar receiver. No shore-based installations such as reflectors or transponders are required, through they may be used to enhance the performance of the system, which results in considerable savings in maintenance costs. The main disadvantage is the amount of processing that is involved. With the availability of high capacity memories and faster processors, this can be overcome. The system design and cost factors of an image correlation system are discussed in a later section.

3.2.3 AZIMUTH MICROWAVE LANDING SYSTEM (MLS)

The azimuth angle measurement portion of MLS may be used as a positioning system by employing several MLS azimuth transmitter and antenna systems along the shore and a directional antenna and receiver on the ship. The maximum operating errors of such a system are specified as .05 deg noise and .03 deg bias [24]. Assuming that the bias is compensated in the processor, the noise of .05 deg produces an error of approximately 0.87m per km or about 7 m for a range of 8 km. By using three stations for a position fix and ensuring a good geometry of operation, the required accuracy may be obtained.

The scan range of the azimuth MLS is ±60 degrees and the size of the antenna is about 1.83 m x .91 m (6 ft x 3 ft.) Since the operation of the system is limited by line of sight, the antenna must be positioned at a fairly high platform, in order to obtain a range of about 8 km. This introduces problems of maintenance. In addition, there can be serious multipath problems because of multiple reflections from the water surface as well as vertical features. The receiving antenna on the ship must also be located at a suitable height to avoid blockage. Because of the complexity in installation and operational limitation due to multipath effects, this system is not useful for channel navigation.

3.2.4 RADIO DIRECTION FINDER (DF) SYSTEMS

Direction finding systems operate in the VHF-UHF band of frequencies, using a multi-element antenna array, multi-channel receiver and processor. If the DF systems are located on land, at least two direction finders are required to determine the location of a shipborne transmitter. The location of the transmitter is obtained from the intersection of the lines of position (LOP) extending from both direction finders, whose location coordinates are known. An operational set-up may include a simple transmitter on the ship with shore-based DF systems. A better choice is to have a single DF station located on the ship with shore-based CW transmitters.

Commercially available DF systems have accuracies of the order of ±1 degree. . For example the Rohde & Schwarz PA 055 VHF-UHF broadband Doppler direction finder covering the 20 to 1000 MHz frequency range has a standard deviation $\sigma \leq 1°$ at a received field strength of 10 dB above the given sensitivity level (e.g., 0.7 μV/m at 150 MHz), and an averaging time of 1 second [25]. The Servosea Model 7010M of Servo Corporation of America, operating between 150 and 175 MHz with 16 wide aperture Doppler type elements, has an instrumental accuracy of ± 1 degree. With this angular accuracy, the positional error is about 7 m at a range of 400 m and increases proportional to the range. Because of the above limitation in angular accuracy, the range of useful operation of the DF system for channel navigation and positioning is severely restricted. In addition, multipath effects can introduce ambiguities in measurement. Transmitters operating at the UHF-VHF band are likely to cause interference with other local transmitting stations and it is difficult to obtain licencing for operation in this frequency band. For the above reasons, DF systems are dropped from further consideration for Seaway navigation.

4.0 TRACKING & DISPLAY SYSTEMS

The location systems discussed earlier provide the position co-ordinates of the ship relative to a known fixed reference. In the case of ranging systems, the location is obtained by measuring the range to three or more reflectors or transponders located at accurately surveyed sites on the shore. In the image correlation system, the location is obtained as a displacement vector relative to a fixed reference point located at the centre of the reference image. The update rate of the positional information is dependent on the type of location system used. In radio ranging systems the update rate is about 0.5 sec, whereas in systems using the radar with a scan rate of 30 rpm, the update rate is 2 seconds. A ship moving with a speed of 8.5 knots travels a distance of 8.75 m in 2 seconds, a distance which is larger than the allowable positioning error in the channel. When combined with the location system inaccuracy, the resulting error in position could be quite high, making the system unusable. Since the ship's motion can be assumed to be continuous within an update interval, its instantaneous position can be predicted to a better degree of accuracy by extrapolation of previous position information, with the help of a tracking algorithm.

The display system acts as an interface between the location system and the human operator. The position and heading information must be conveyed in real-time to the navigator, to help in navigating the ship along the channel course line. One efficient means of presenting this information is by using a graphical display, which shows graphically a map of the channel and the location and heading of the ship in the channel. This may be implemented using an electronic chart display, which is fed with digitized map information on different portions of the Seaway. The map information can be stored on a digital storage medium, which is portable and readily updatable. The display system must be provided with a suitable interface to accept the position information from the location system. It is also particularly desirable to overlay the radar image on the electronic chart in order to continuously monitor the performance of the positioning system as well as observe other ships in the vicinity.

4.1 TRACKING ALGORITHM

The tracking problem for ground-based tracking radar has been studied in detail by other researchers [22]. Tracking radars often use either monopulse or track-while-scan techniques. For a navigation system, the tracking problem can be considered as the inverse of the ground-based radar target tracking problem, where instead the radar is static and the targets are moving. The nature of the tracking scheme can be similar for any ranging technique, i.e., radio ranging, radar with polarization discrimination and radar with transponders or DME, since all these techniques use the range values to a set of reference targets located on the shore.

The formulation of a tracking algorithm for a typical ranging system is illustrated in Figure 4-1. Since the geometry of the targets is known, the track processor can be fed with the range and azimuth information, during start up, indicating the approximate location of the targets in view. Targets detected near these locations are identified as reference targets, and a track initiation takes place, to track each target individually. The ship's position is determined by inverse trilateration and a track is initiated to continuously track the ship's position. Using smoothed position and velocity values based on ship's dynamics, the position of each target for the next scan is predicted with the help of a tracking filter. The predicted target locations are used as inputs for target detection and track association for the subsequent scan. By continuously tracking each target, the results can be tested for consistency and the best geometry can be selected for trilateration, to limit the GDOP. The ship's heading must also be monitored continuously to check for consistency in the gyro output data and to ensure that the required minimum clearance is available to the shoreline from the fore and aft ends of the ship.

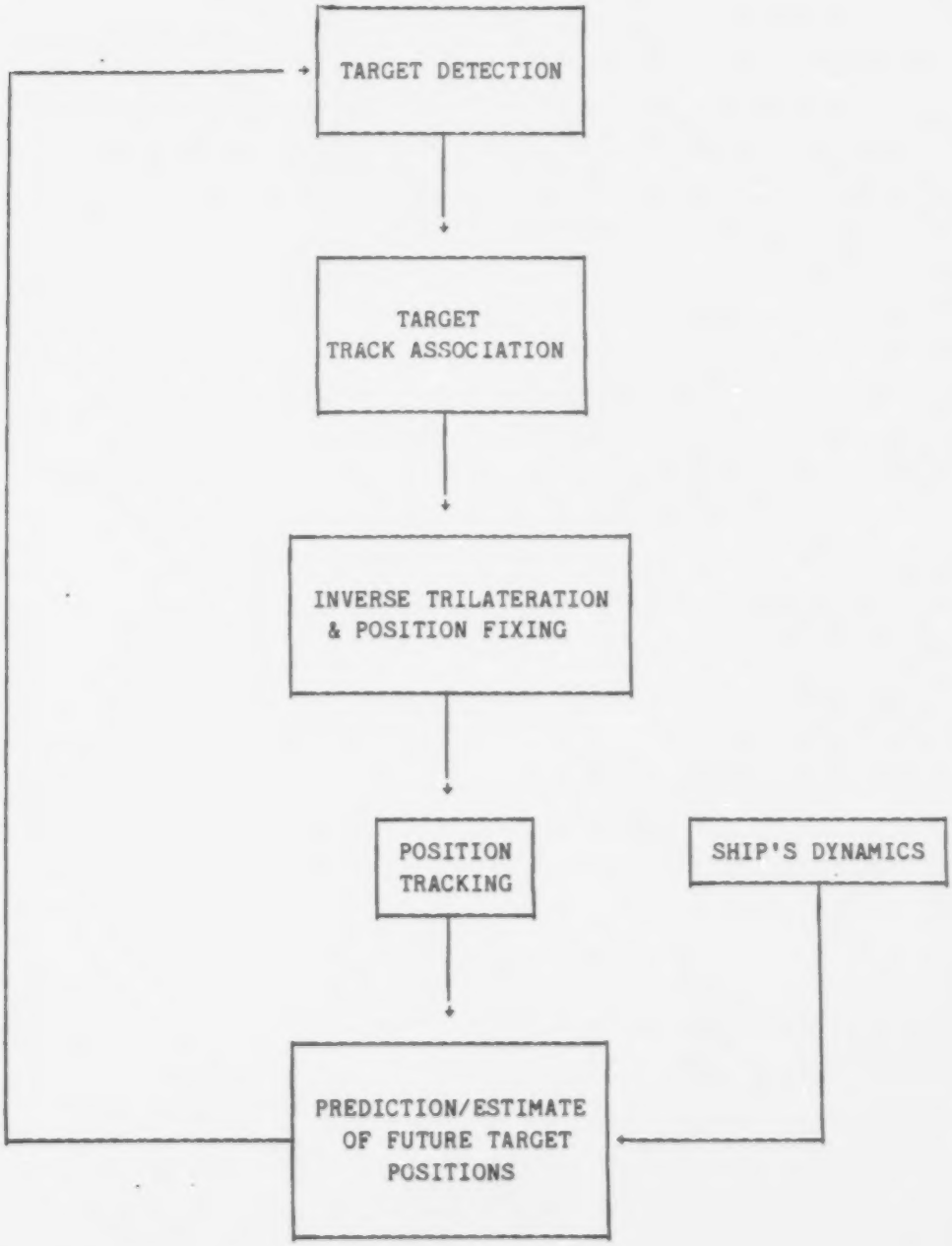


Figure 4-1 Tracking Algorithm

On the basis of previous target detection the track-while-scan radar must make a smoothed estimate of the target's present position and velocity, as well as a predicted position and velocity. A standard method for doing this is by using an α-β tracker, which computes the present smoothed position $\bar{x}_n$ and velocity $\dot{\bar{x}}$ by using the following equations [22]:

$$\bar{X}_n = X_{pn} + \alpha(X_n - X_{pn})$$

$$\dot{\bar{X}}_n = \dot{\bar{X}}_{n-1} + \frac{\beta}{T_s}(X_n - X_{pn})$$

where X_{pn} = predicted position of the target at the nth scan,
X_n = measured position at the nth scan,
α = position smoothing parameter
β = velocity smoothing parameter, and
T_s = time between observations

The predicted position at the n + 1st scan is $\bar{X}_n + \dot{\bar{X}}_n T_s$. When acceleration is important, an $\alpha - \beta - \nu$ tracker may be used by adding an extra equation for computing the smoothed acceleration. This is not required for Seaway navigation because the ship's motion will be relatively uniform due to its large size. For $\alpha = \beta = 0$, the tracker uses no current information, but only the predicted output from previous observations. If $\alpha = \beta = 1$, no smoothing

is done using predictions from prior information. The classical α - β filter is designed to minimize the mean square error in the smoothed position and velocity. It is assumed that the velocity changes between observations is small and the target is not a maneuvering target. Several methods have been suggested for choosing the values of α and β coefficients. To minimize the output noise and variance and assuming a ramp function transient response for a maneuvering target, a suggested relationship between the coefficients is given by $\beta = \alpha^2(2 - \alpha)$. The choice of α depends on the tracking bandwidth. The compromise is between smoothing of random measurement errors with narrow bandwidth and rapid response to maneuvering targets at high bandwidth. Another method is based on the best linear track fitted to the radar data in a least squares sense, which gives the α and β coefficients as follows:

$$\alpha = \frac{2(2n-1)}{n(n+1)} \qquad \beta = \frac{6}{n(n+1)}$$

where n = number of the scan or observation (n>2). In an adaptive α - β tracker, the smoothing parameters are varied in order to vary the bandwidth and follow target maneuvers. The value of α is set by finding the measurement error $X_n - X_{pn}$. The bandwidth is made wide at the beginning of tracking and is narrowed down if the target moves in a straight-line trajectory. The bandwidth is widened as the target maneuvers or turns, to keep the tracking error small.

The Kalman filter [26] is similar to the standard α - β tracker. It uses a model for the measurement error and for the target trajectory. A realistic dynamic model would include the dynamics of ship motion, measurement noise, heading errors, trajectory disturbances due to current etc. By considering higher-order derivatives in the model of the dynamics, random errors in measurement and target trajectories, the Kalman filter can be made quite sophisticated and accurate enough to handle a dynamic situation. If the modeling of the target trajectory is assumed as a straight line and the measurement and trajectory disturbance errors assumed

as white gaussian noise with zero mean, the Kalman filter equations reduce to the standard α - β filter equations, with parameters α and β computed sequentially by the Kalman filter procedure.

The error between updates is dependent on the maneuvering capability of the ship. For a bulk carrier, the radius of the turning circle is about 1.32 times the length of the ship. A ship of length 280 m, moving with a velocity of 3.8 m/sec (7.4 knots) is capable of executing a turn with an acceleration of $a = v^2/r = 3.8^2/(1.32 \times 280) = .04$ m/sec^2, where 'v' is the ship's velocity and 'r' is the radius of the turning circle. If the update time interval is Δt, the peak value of the positional error between updates is given by:

$$\frac{1}{2} a (\Delta t)^2 = .02 \Delta t^2 \text{ metres}$$

This positional error is quite small, i.e.: 2 m for an update interval of 10 seconds.

A more important consideration is the rate of turn. A typical value for turning rate is 0.6 degree per second. If the update interval is 2 seconds, the turning of the ship during this interval causes an error in the clearance to the shore from the fore and aft of the ship of:

$$\pm \frac{1}{2} \sin (0.6^\circ \times 2) \times 280 \text{ m} = \pm 3.08 \text{ m}.$$

Additional inputs to the tracking system from sensors other than the location system can help in improving the tracking system performance. The gyro compass and speed log outputs can be quite useful in this regard. The gyro output provides continuous information on the ship's heading. The speed log measures the speed through water or the speed over ground. This additional information may be used for cross checking the performance of the tracking algorithm.

Starting or termination of track can be decided by the tracker, since the tracker has a prior knowledge of the relative positions of all the targets, which are fixed. In this sense, the tracking problem is less severe here than in the case of standard tracking radars. Degradation of tracking performance is easily monitored by calculating the measurement error $(X_n - X_{pn})$ for each target as well as for the ship's position.

4.2 DISPLAY SYSTEM

Two display types were described in Section 2.2 on display requirements, a digital display of navigational information and a graphic display illustrating the position and orientation of the ship on an electronic chart. The display requirements have been studied in previous channel navigation studies, i.e., the requirements listed in Section 2.2 are mainly based on the German & Milne report [2], which are in turn derived from the requirements listed in other earlier studies [27, 28]. The secondary use of a navigation system for vessel management, as discussed in [28], is not considered as a requirement for the system, although it may be advantageous. In order to help the navigator locate other vessels in the vicinity, and to increase the operator's confidence an overlay of the radar image on the graphic display is recommended.

4.2.1 DIGITAL DISPLAY

The information required for navigation includes the position of the vessel in the channel with respect to the course line, distance and time to the next turning point or way point, attitude in the channel and true speed [28]. Referring to Table 2.2-1, the ship's attitude in the channel is defined by the channel course line in degrees and the ship's heading as given by the gyro. The ship's position with respect to the course line is indicated as the minimum distance to the channel limit available on the left and right sides of the ship. This also takes into account the attitude of the ship in addition to its position in the channel, which is quite important. Indicating the minimum available clearance rather than the distance from the course line is helpful during turning maneuvers and ship crossings. In addition to the above information, Table 2.2-1 also lists the course line's next reach, which indicates the angle by which the ship is required to turn when it reaches the next way point. The information on the channel course line for all reaches can be provided as stored chart data in the system.

In a navigation system using the ship's radar, the scan update interval is typically 2 seconds. A faster display update rate may be achieved, when using shore-based targets, by using the tracking system to update the position every time a target is detected. In the image correlation scheme, sector processing may be used for a faster update rate. The update rate for a radio ranging system with interrogators on-board the ship and transponders on the shore is dependent on the number of interrogators operating in a short stretch of the channel. In the case of a radio location system, where the ship's equipment consists only of a passive receiver, the traffic density is not a problem. A two second update time is considered sufficient, based on the analysis in Section 4.1.

4.2.2 GRAPHIC DISPLAY

Even through a simple digital display presents all the information needed for blind navigation along a course line, it does not present any information on other features in the channel or other ships in the vicinity. A graphic image illustrating the relative position and orientation of the ship on a map of the channel overlaid on a radar image displays all the needed information including the position of other ships or marker buoys in the channel. (This also helps in verifying the performance of the location system with the ship's radar output). The digital display should be integrated with the graphic display, for example, by showing the digital information at one corner of the picture.

There are three possible representations of the graphic image, as follows:

Option (1): Course line vertically up,
Option (2): True North up, and
Option (3): Ship's head up.

It is convenient to have the ship positioned always at the centre of the image, since the user is accustomed to this orientation because of the normal radar PPI.

For option 1, the orientation of the electronic chart is fixed for any particular reach and the chart moves down vertically until the next way point is reached. This is easily accomplished on a graphic display with a video memory. If the ship is to be centred on the image, the course line will move away from the centre as the ship is laterally displaced. In other words, the chart must be laterally moved to accommodate this displacement. This can be done by using a moving pointer for horizontal read out from the video memory. With course line up and the ship at the centre of the image, the only operation required is a two-dimensional translation of the chart image. The radar overlay involves rotation of the radar image by an angle equal to the difference between the ship's heading and the course line angle. Since the radar image is in range-azimuth form, a rotation can easily be performed on this image before scan conversion to Cartesian co-ordinates.

In options 2 and 3, the electronic chart needs to be rotated to coincide with the required orientation. This operation is more complex and needs a high resolution chart in order to limit errors due to image rotation. The radar can be switched to display either North up or the ship's head up. The only difference in options 2 and 3 is the angle by the chart image must be rotated to coincide with the radar image. The axis of rotation is defined by the location of the ship.

While options 2 and 3 may be favoured by the master of the ship, because of familiarity with radar displays, option 1 is recommended because of its computational simplicity.

The principal use of the graphic display is to qualitatively illustrate the relative position of the ship in the channel. It cannot indicate, to a high degree of accuracy, position information, as does the digital read-out. However, the graphic display must have adequate resolution to display the electronic chart in full detail, as well as to display the radar image in sufficient resolution at its minimum range scale. Full scale ranges may be selected as ½, 1, 3, 6 and 12 nautical miles. For a full scale range of ½ nmi, a resolution of about 3.6 m is obtained with 256 pixels along a range line. This gives a 512 by 512 pixel resolution for

the graphic display, which is likely to be sufficient for displaying an electronic chart. With extra resolution, the pixel size becomes too small to be distinguishable. Standard 512 x 512 Red-Green-Blue (RGB) video monitors are available, which can be directly interfaced to video memory boards. The memory boards can be updated by the processor at the tracking update interval.

Figure 4-2 shows a typical representation of the ship's location on a graphic display, with the ship located at the centre of the image and the course line displayed as a vertical straight line. The previous ship positions and orientations are shown marked as dotted lines. These may be marked at regular time intervals or spatial intervals along the course followed by the ship. By marking at regular time intervals, the display also indicates roughly the velocity of the ship. For example, choosing a 4 minute update for the previous ship positions, the displacement would be about 122 pixels for a ship speed of 7.4 knots (3.8 m/sec) and about 82 pixels for a speed of 5 knots for a pixel size of 7.5 m. This size of the display and "mark" interval might be made selectable in steps to make the display easier to use.

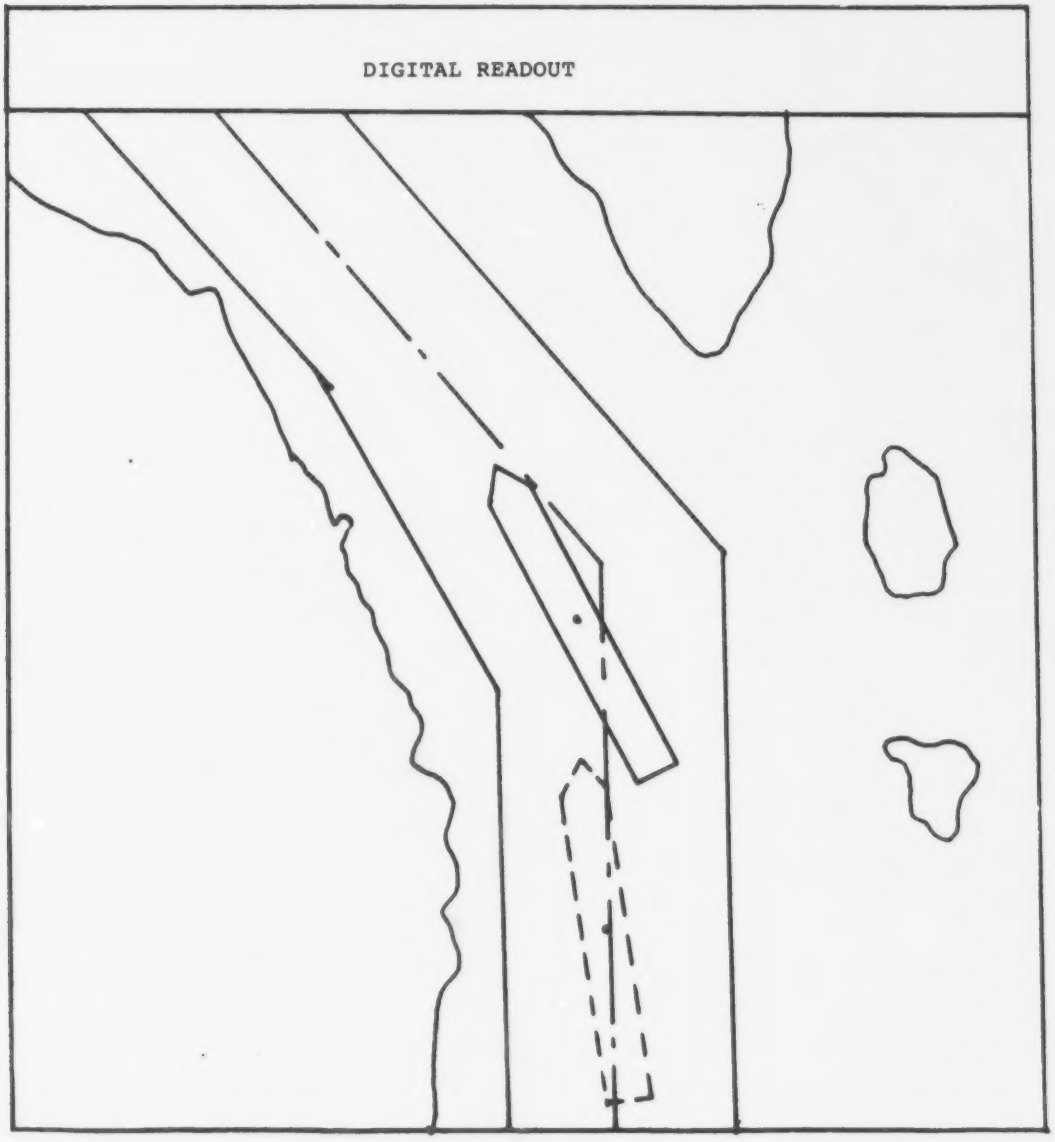


Figure 4-2 A Typical Graphic Display

5.0 SYSTEM CONFIGURATION

As a result of the analysis performed in Section 3, the following location systems were found to be technically suitable for channel navigation purposes:

(1) Ship's radar using image correlation,
(2) Ship's radar with polarimetric reflectors,
(3) Ship's radar with transponders, and
(4) Radio ranging system (UHF or microwave).

The differential GPS system has been intentionally omitted from this list because it is currently not operational to the extent required, and may not be before 1991. However, once the GPS does become operational it becomes highly probable that, even with the purposeful system accuracy degradation which can be expected, the technique will yield accuracy which is acceptable. Therefore, some preliminary comments on possible implementation and associated costs are included later in this section, for the sake of completeness.

The cost-performance tradeoff for these options should be carried out by looking at the detailed system configuration applicable for the entire St. Lawrence Seaway for each of the options. Since this is quite involved, a relative cost comparison is made based on the following:

(1) The costing is done only for a few typical reaches and the results generalized for the Seaway.

(2) As far as possible all the systems are compared for configurations which would give similar performance.

(3) The tracking and display subsystems are assumed to be identical for each of the four cases and are not included in the comparison.

(4) Wherever information is not available, assumptions are made.

For each of the 4 technically suitable systems a block diagram showing the key subsystems is provided, together with a technical disucssion of the major factors which must be considered in a cost analysis.

Although it would be most desirable to determine the cost of each of the 4 systems, time and financial limitations to this study preclude such an approach. Therefore it was decided to estimate the relative costs of each approach and then estimate the total cost of the least costly approach. Section 5.6 contains the results of this computation.

The St. Lawrence Seaway is comprised of 83 reaches from St. Lambert lock to Wolf Island, Kingston, the details of which are available in the plans prepared by the St. Lawrence Seaway Authority [29], and reproduced in this report as Appendix A. Two typical stretches are considered for sample evaluation, as follows:

Reach Nos.	Reach Length (Stat Miles)	Turning Angle (Deg.)	Channel width (m)
25 to 28	0.9 to 1	27 to 42	137 to 213
20,21,22	1.4 to 2.5	19.5 to 21.5	137

The stretch containing reach numbers 25 to 28 is considered as a difficult portion of the channel involving severe turns and short reaches, while the stretch containing reaches 20, 21 and 22 is considered a typical portion with normal turning angles and reach lengths. The results obtained for these two stretches are extrapolated to cover the entire 307 km length of the channel.

5.1 RADAR IMAGE CORRELATOR

The image correlation technique or the clutter mapper compares the image produced by the ship's radar with one of several stored radar images obtained at several calibrated reference points along the course line, and computes the displacement vector with respect to a particular reference point. The comparison of the two images is done by correlation. The ship's radar image is displaced pixel by pixel in the X and Y directions and the correlation coefficient is computed for each displaced position. The displacement vector which produces the maximum value for the correlation coefficient gives the position of the ship relative to the reference point. The position is refined by finding the centre of gravity for a matrix of correlation coefficients, thereby obtaining a resolution better than the basic pixel resolution.

If the ship speed is assumed as 5 knots (2.5 m/sec), and the scan update time for the ship's radar is 2 seconds (30 rpm antenna rotation speed), then the ship moves by about 5.14 metres in one update period. If the pixel resolution is assumed as 7.5 m, the ship's movement is about one

pixel for each update. By using a resolution of 512 by 512 pixels for the reference image, a radius of 1.92 km can be covered by a single reference image. With a 50 percent overlap between adjacent reference images, a length of course line equal to 1.92 km is covered by the overlapping region. A ship located midway between reference images 1 and 2, can use a 256 x 256 pixel image for correlation with either reference image 1 or 2. This covers a circular region of radius equal to 128 x 7.5 or 960 m. The reference image 1 can be used for correlation as the ship moves from point 1 to point X, and image 2 used for the region between points X and 2. For a distance between two reference points of 1.92 km, and a total course line length of 300 km, 157 reference images will be required. In order to better accommodate sharp turns and different viewing aspects (i.e., effect of blockage by chips, etc) a total of 200 reference radar images is assumed.

The reference images can be stored on compact laser discs as disc files and retrieved by the processor whenever required. The size of each disc file is 512 x 512 or about 262 K pixels and for 200 images, a total capacity of 52.5 M pixels is required. A pixel resolution of 4 bits is assumed therefore the memory requirements equal 0.21 Gigabits.

Each computation of the correlation coefficient requires 256 x 256 multiplications and additions. The system first computes the correlation coefficient, using a displacement approximately given by the prediction algorithm used for tracking. Next, the image is shifted around this mean position and correlation coefficients are computed for each shift. A correlation coefficient matrix of either 3 x 3 or 5 x 5 may be computed, centered around the first computation. Assuming a 5 x 5 matrix or 25 computations of the correlation coefficient, a total of 25 x 256 x 256 or 1.64 M multiplications and additions must be performed for each update. The position of the centre of gravity is computed from the matrix of correlation coefficients and declared as the ship's location.

Because of the extensive computations involved in the correlation process, a vector processor such as an array processor or special purpose hardware may be necessary. The image may be processed quadrant by quadrant

if it should be necessary to avoid blockage or poor correlation in certain sectors or speed up the update rate. At the beginning of tracking, the system must be started with a known approximate location so that it can do a preliminary search and find the true position. If the input location is off by ±250 m, then the area to be searched for obtaining the true location is 67 x 67 pixels, with a pixel resolution of 7.5 m. the system must perform at most 67 x 67 or 4489 correlations, before it can find the true position. Assuming that 25 correlations can be performed in less than the update time of 2 seconds, it would take about 6 minutes to do this initial search.

The correlation technique will not work well in areas of open water, where most of the image is devoid of features. Since correlation is mainly useful for features on land, the area covered by water may be masked from correlation. This approach also avoids clutter in the near range of the ship, for which the radar receiver is saturated and therefore of little value. When using the correlation technique in lakes, as for example, in reaches 25 to 28, it is necessary to offset the image correlation so that the comparison covers mostly land features rather than open water. This could easily be done by splitting the image into two halves such that each half covers the land area close to the shoreline on either side of the lake.

In narrow reaches, as in the case of reaches 20 to 22 which involve sharp turns, it will be necesasry to have more references image in order to account for shadowing by tall vertical features such as large rock or heavily treed islands.

A block diagram of the image correlation system is shown in Figure 5.1. The system accepts the radar trigger, video and azimuth signals from the ship's radar. The digitizer and video processor is used to process the analogue video input signal and produce digitized range pixels. Its principal functions are as follows:

(1) Sampling and digitizing the analog video,

(2) Applying a Sensitivity Time Control (STC) along the range,

(3) Cancelling interference by pulse-to-pulse correlation,

(4) Adaptive thresholding using a Fast Time constant (FTC) circuit, which acts as a high pass filter or differentiator, and

(5) Pulse-to-pulse averaging, which suppresses noise.

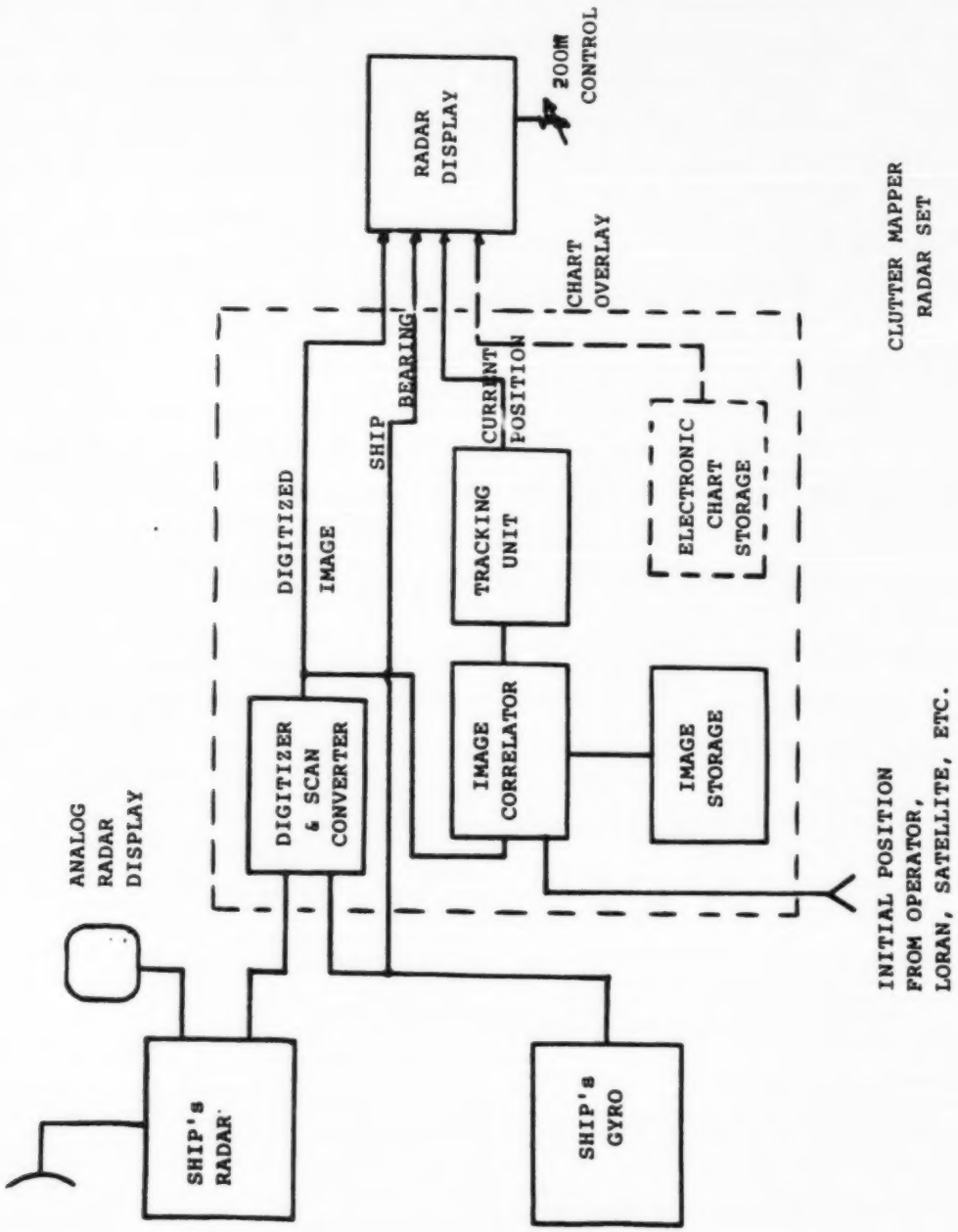


Figure 5.1 Image Correlation Radar

The FTC and STC functions may alternatively be implemented in the analog domain prior to digitization. The pulse-to-pulse correlation and averaging should be carried out digitally. The required minimum sampling rate, for obtaining a pixel resolution of 7.5 m in the final image, is 20 MHz. Oversampling may be used to reduce the effects of noise and scan conversion errors. For example, a sampling rate of 40 MHz may be used and by averaging two pixels in the image, the resolution may be reduced to 7.5 m. Holes in the final image resulting from scan conversion, at long range, may be suppressed by repeating radials between two adjacent azimuth returns. The scan conversion would be implemented in hardware in order to speed up computation and operate in real-time. Isolated pixels in the image, resulting from noise, may be deleted, in order to reduce the correlation error. The output image used for correlation has 256 x 256 pixels, with a pixel resolution of 7.5 m in both X and Y directions.

The processed image is transferred to the video memory and used for correlation. The reference image from the disc memory is also transferred to high speed memory prior to data acquisition, so that no time is lost in data transfer. If desirable, the correlation may be performed quadrant by quadrant, in order to increase the scan update rate by four times. The image obtained with the 40 MHz sampling rate can be displayed on the TV monitor as a 512 x 512 image.

The image displayed on the TV monitor would generally be colour coded for pixel intensity and the colour code information is displayed in one corner of the monitor screen. A zoom feature should be included for better perception of details in the image. The image should be oriented such that the ship is always positioned along the horizontal centre line and the course line coincides with the vertical centre line.

The location algorithm computes the centre of gravity position for 5 x 5 coefficient matrix centred around the predicted position. This information is fed to the tracking algorithm which computes the predicted position and velocity. This information can then be presented at one corner of the display along with other navigation information listed in Table 2.2. The specifications of the image correlator are summarized in Table 5.1.

Table 5.1 Specifications of the Image Correlation System

1. Digitizer & Video Processor:

Sampling & A/D rate:	40 MHz, 6 bit
Processing:	FTC, STC Interference Cancellation, Pulse-to-pulse integration
Interface:	Ships's radar trigger, raw video, and azimuth gyro input

2. Scan Converter:

Input: 512 range bins at 40 MHz rate
Output: 512 x 512 image

3. Computer:

High speed floating point processor.
Adequate memory for storage.
DMA interface to scan converter.
Interfaces to disc, video memory & console.

4. Disc:

Compact disc with capacity to store a minimum of 200 reference images, each of size 512 x 512 pixels, with 4-bit resolution.

5. Video Memory:

512 x 512, 4-bit capacity for each image

6. TV Monitor:

Red-Green-Blue (RGB) colour monitor with sufficient bandwidth to display 512 x 512 colour coded 4-bit pixels. Zoom feature

7. Reference Image Format:

512 x 512, 4-bit pixels with a pixel resolution of 7.5 m in both X and Y directions. Max. of 200 images covering the channel course line length of about 300 km.

Table 5.1 Specifications of the Image Correlation System (cont'd)

8. Radar Image for Correlation:

   256 x 256, 4-bit pixels correlated with the corresponding sector of the reference image.

9. Location Algorithm:

   5 x 5 matrix of correlation coefficients used to compute the centre of gravity point.

10. Tracking Algorithm:

    Predictive filter to compute smoothed position and velocity.

11. Tracking Accuracy:

    Position accuracy: better than ±7.5 m.
    Velocity accuracy: better than ±0.3 m/sec.

12. Display Information:

    Ship's location along horizontal centre line, with channel course line coinciding with the vertical centre line.

    Colour coding details displayed at one corner of the screen, and digital display at another corner, indicating the channel course line in degrees true, ship's head, speed over ground, distance to next way point, time to next way point, course line next reach in degrees true and minimum distance to channel limit on both sides of the ship.

5.2 POLARIMETRIC REFLECTORS WITH MODIFIED SHIP'S RADAR

The polarization discrimination scheme discussed in Section 3.2.2.3.1 uses passive polarimetric reflectors which reflect a cross-polarized signal. Horizontal polarization is transmitted by the ship's radar and vertical polarization is received back, therefore, an additional vertically polarized receive antenna is required on the ship to receive the cross- polarized returns from the reflectors.

A modified ship's radar system for receiving cross polarized returns is illustrated in Figure 5.2. A vertically polarized receive antenna is added on top of the original horizontally polarized antenna on the ship's radar, such that the two are synchronized in rotation. A second rotating joint is necessary for the vertically polarized signal which is then connected to a second radar receiver to detect this signal. The radar trigger, video and gyro signals are fed to the digitizer for signal processing and target detection. The detected target information is transmitted to the computer which correlates the detected target locations with predicted positions and computes the location of the ship, which is sent to the graphic display.

An alternative scheme requiring minimal additions to the ship's radar system for receiving cross polarized returns, is illustrated in Figure 5-3. The vertically polarized receive antenna is added as before, however, a second rotating joint is avoided by using a PIN switch which alternates between the two antennas for transmission and reception. The radar trigger, video and gyro signals are fed to the digitizer for signal processing and target detection. The detected target information is transmitted to the computer which correlates the detected target locations with predicted positions and computes the location of the ship which is sent to the graphic display. In order to keep the radar system and the display working normally, the switching is done only for alternate radials. The antenna selector receives the PRF and reference signals and switches the vertically polarized antenna in for alternate radar trigger pulses, during the receive period. The command to switch the antenna outputs, issued by the antenna selector, is transmitted to the PIN switch through a slip ring.

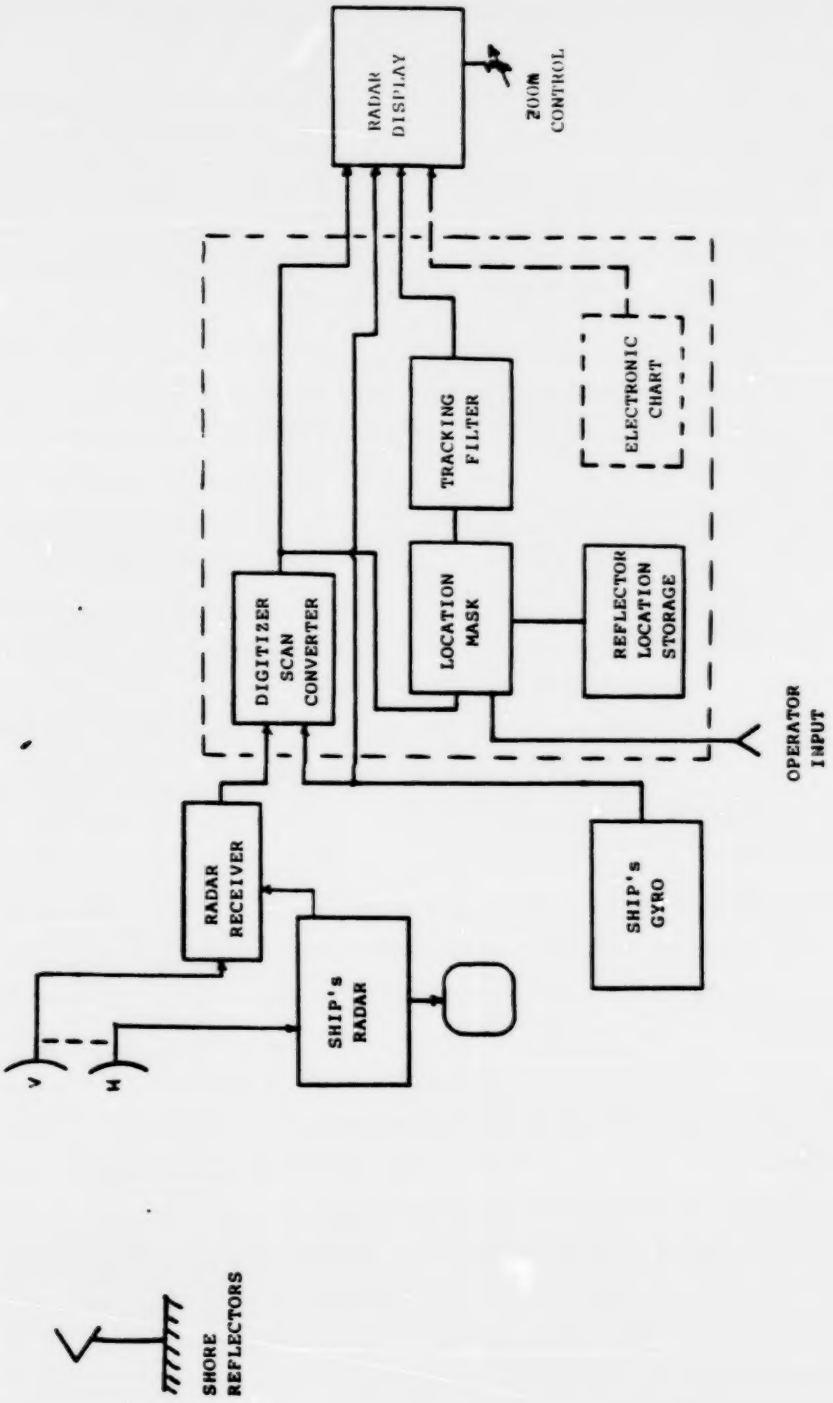


Figure 5.2 Polarimetric Radar Block Diagram

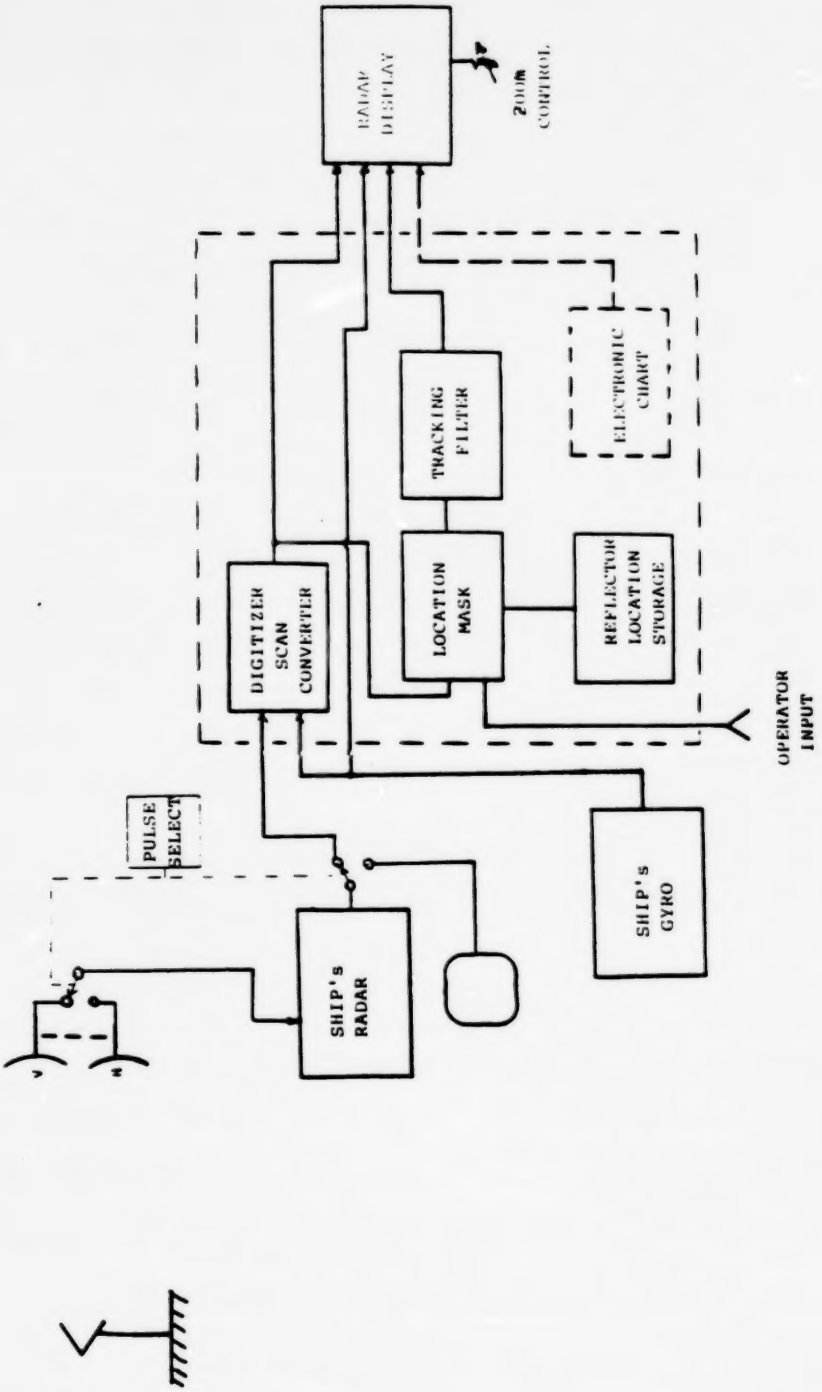


Figure 5-3 Alternative Polarimetric Radar Block Diagram

There are two drawbacks to this alternative system. The radar receiver output consists of returns for horizontal and vertical polarization components for alternate pulses, therefore the performance of the radar display will be affected because of the lower intensity of the vertically polarized returns, therefore the radar display screen would appear less bright than normal. The second disadvantage is that only half the number of pulses are now available for pulse-to-pulse averaging. This would affect the signal-to-noise ratio (S/N) of the vertically polarized returns used for detecting the reflectors. The advantage of this approach is reduced cost, since the additional rotating joint and radar receiver are not required. Since the ship's master may not accept a reduction in radar performance, this alternative was not considered further.

The size of the shore mounted polarimetric reflectors depends on the maximum range at which these reflectors are to be detected. The maximum range in turn depends on the geometry of the channel and the triangulation geometry. Figure 5-4 illustrates the geometry for a straight channel. The reflectors are positioned on either side of the channel in an alternating fashion, as shown in the figure. With the ship positioned as shown in the figure, reflectors 1, 2 and 3 are used for trilateration. As the ship moves ahead, the reflectors 2, 3 and 4 are used. If the number of reflectors is to be conserved, the reflectors must be positioned as far away as possible from the shore line inland. But this would increase the size of the reflectors because of the longer range. In addition, they have to be positioned at sufficient height, so as to avoid any blockage due to the terrain or vegetation. This involves a trade-off between the size and height of reflectors and the number of reflectors. Additional reflectors will be required near way points and stretches where ships are allowed to pass each other.

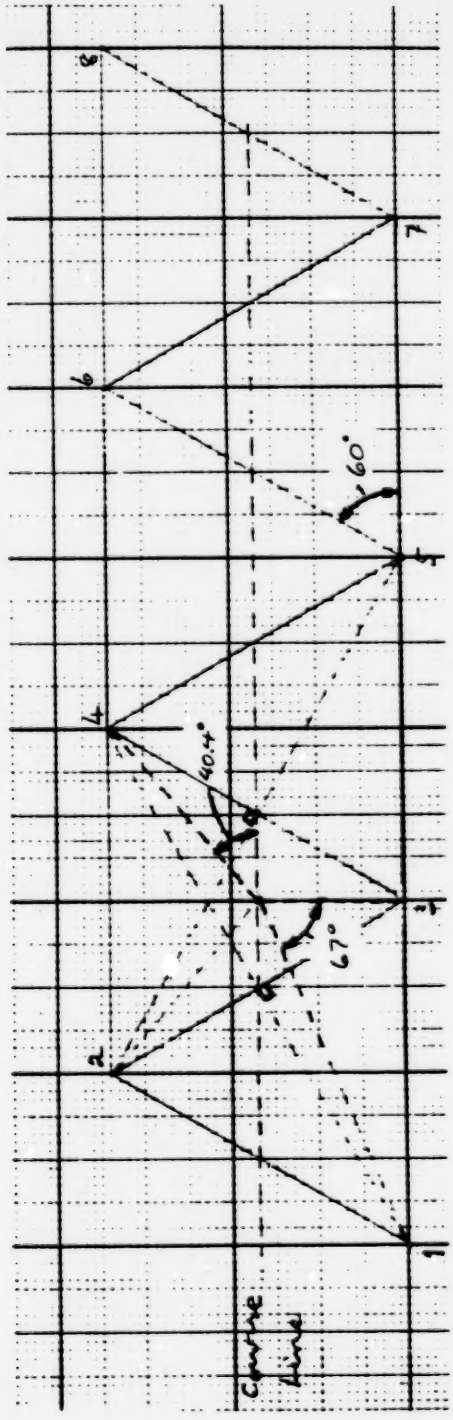


Figure 5-4 Trilateration Geometry

Some considerations regarding the location of retros are listed below:

(1) The ship's radar assumed to suffer from blockage at certain azimuth angles due to the mast, superstructure and the funnel. This blockage is estimated to be 20° on either side of the fore and aft line of the ship, or an arc of 40°.

(2) The azimuth angle between two reflectors, shown as θ_{az} in Figure 5-5, must be equal to 90° for optimum trilateration error. From Section 3.2.2.1, the two components of trilateration error are given by:

$$\sigma_r' = \frac{C_e' \sigma_r}{2 \cos \alpha} \quad \text{and} \quad \sigma_n = \frac{C_e \sigma_r}{2 \sin \alpha},$$

where $C_e = C_e' = \sqrt{2}$, $\alpha = \theta_{az}/2$,

σ_r = range error (assumed as 3m).

The value σ_r' and σ_n represent the semi-minor and semi-major axes of the error ellipse, as shown in Figure 3-4. The errors are tabulated as a function of θ_{az} in Table 5-2, and plotted in Figure 5-5. In order to limit the position errors, a range of 45° to 135° is used, which limits the errors to 5.5m.

Table 5-2 Position Errors as a Function of θ_{az}

θ_{az} (deg.)	σ'_r (m)	σ_n (m)
5	2.12	48.63
10	2.13	24.34
15	2.14	16.25
20	2.15	12.22
25	2.17	9.80
30	2.20	8.20
35	2.22	7.05
40	2.26	6.20
45	2.30	5.54
50	2.34	5.02
55	2.39	4.59
60	2.45	4.24
65	2.52	3.95
70	2.59	3.70
75	2.67	3.48
80	2.77	3.30
85	2.88	3.14
90	3.00	3.00
100	3.30	2.77
110	3.70	2.59
120	4.24	2.45
135	5.54	2.30

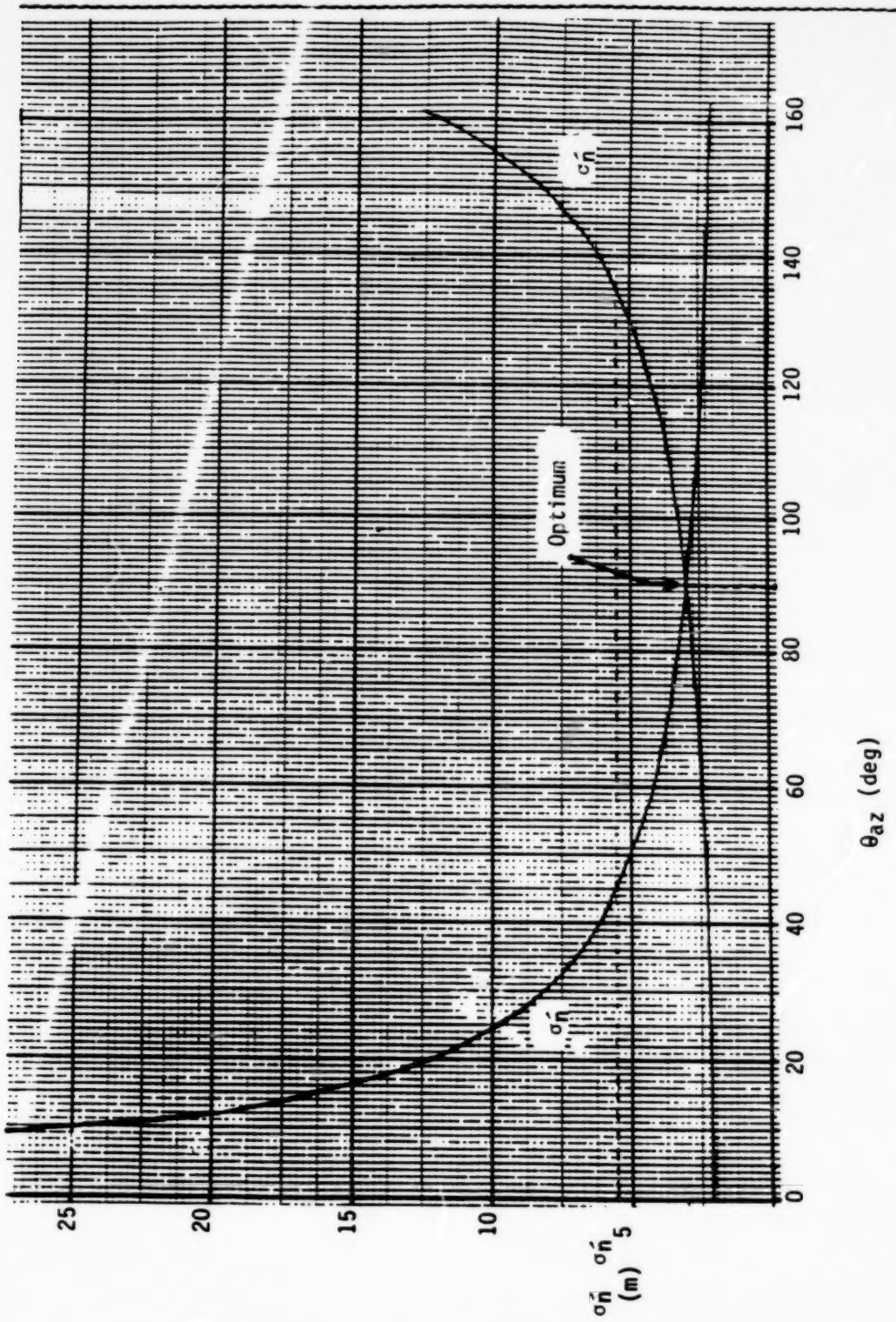


Figure 5-5 Plot of Position Errors as a Function of θ_{az}

An ideal geometry is one in which the reflectors alternate on either side of the course line, with three successive ones forming an equilateral triangle, as shown in Figure 5-6. At point A, the azimuth angles subtended by the reflector pairs 1-2, 2-4, 1-3, and 3-4 are all equal to 90°, and the error is minimum. Same is the case at point C. At point B, the angles are 63.4, 99.2, 67 and 130.4 degrees respectively. The error due to the fourth measurement may be reduced by using reflector 5.

By using at least four reflectors for measurement, even if there is a blockage of one of the reflectors, due to passing ships or other effects, a minimum of three measurements are available for trilateration. The maximum required range is given by the distance between reflector 1 and point B. If the length of the side of the equilateral triangle is 'x', the maximum range is equal to x/(sin 67°) and the minimum range is given by x/(tan 67°).

3. With the prescribed geometry, the reflectors can be positioned as far apart as required, such that at least a group of four are in constant view of the radar at any time. If the value of 'x' is large, it will be necessary to position the reflectors at a greater height to avoid blockage by land masses or trees. If 'x' is small, a considerably larger number of reflectors are required.

4. The height of the reflector should be limited to a value such that the difference between the radar antenna height and the reflector height does not introduce appreciable slant range errors. For example, if a reflector were positioned at a range of 100 m, and the maximum allowable slant range error is 1 m, then the maximum difference in the height between the reflector and the ship's antenna can be only 14.18 m. A correction for this error can be applied by the processor, if the height information for each reflector is stored in memory.

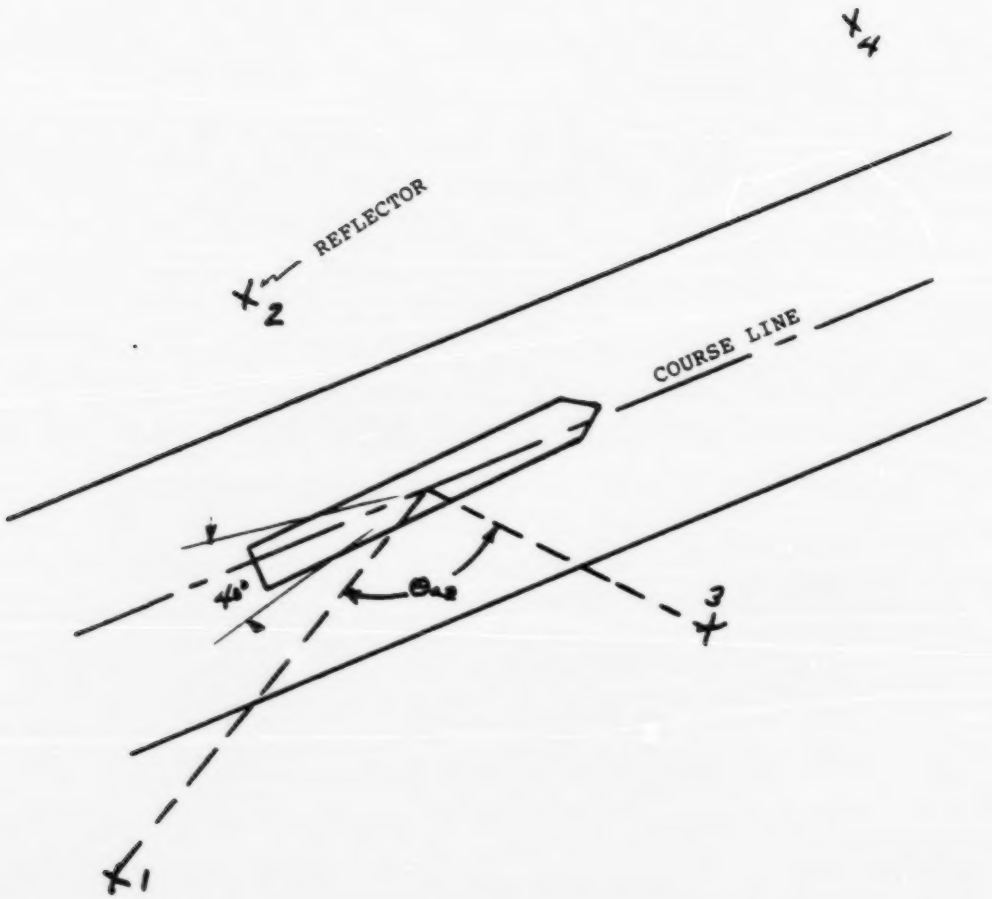


Figure 5-6 Reflector Geometry

The height of the ship's radar antenna can change depending on the ship's loading. This information can be fed to the processor at the commencement of tracking, so that corrections can be applied to the measured slant range.

5. Since maximum accuracy is required as a vessel approaches a way point and prepares to make a turn, the geometry of the reflectors should be optimum for these points. It may be required to use extra reflectors, depending on the severity of the turn.

In order to estimate the number of reflectors, two stretches are all taken for analysis. The first stretch containing reaches 20, 21 and 22 is considered a typical stretch, with mostly open water and long reaches. The second stretch comprising of reaches 25, 26, 27 and 28 is considered as a difficult hard-to-negotiate stretch, with narrow and short stretches with severe turns. A map of the channel indicating approximately the positions of reflectors for stretch is given in Figure 5-7. A similar map for stretch 2 is shown in Figure 5-8. (Only approximate positions are indicated in the figures, as no detailed analysis has been done.) The reflectors are positioned close to the shore line for simplicity. It is seen from the two figures that only about 6 reflectors are need for stretch 1, whereas 17 are required for stretch 2. Because of the wide area covered by the open stretch of water, the reflectors along the shore line in stretch 1 have a maximum range of the order of 5 km from the course line. The maximum range in stretch 2 is around 1.5 km.

The total length of the Seaway, which contains 83 reaches from St. Lambert lock at Montreal to Wolf Island, Kingston, is 191.2 miles or 305.9 km. The reaches may be classified as typical or difficult as shown in Table 5.3, in order to determine the total required number of reflectors. Reaches in open lakes are considered as typical, while all the rest are classified as difficult, because a large number of reflectors are required when they are positioned along the shore line at short range. With this assumption, the total lengths of typical and difficult reaches are 176.5 km and 129.4 km respectively. The average number of reflectors required per kilometre is (6/9.76) for a typical stretch and (17/10.24) for difficult stretch. The required total number of reflectors is 109 for typical stretches and 215 for difficult stretches, or a total of 314 reflectors for the entire length of the Seaway.

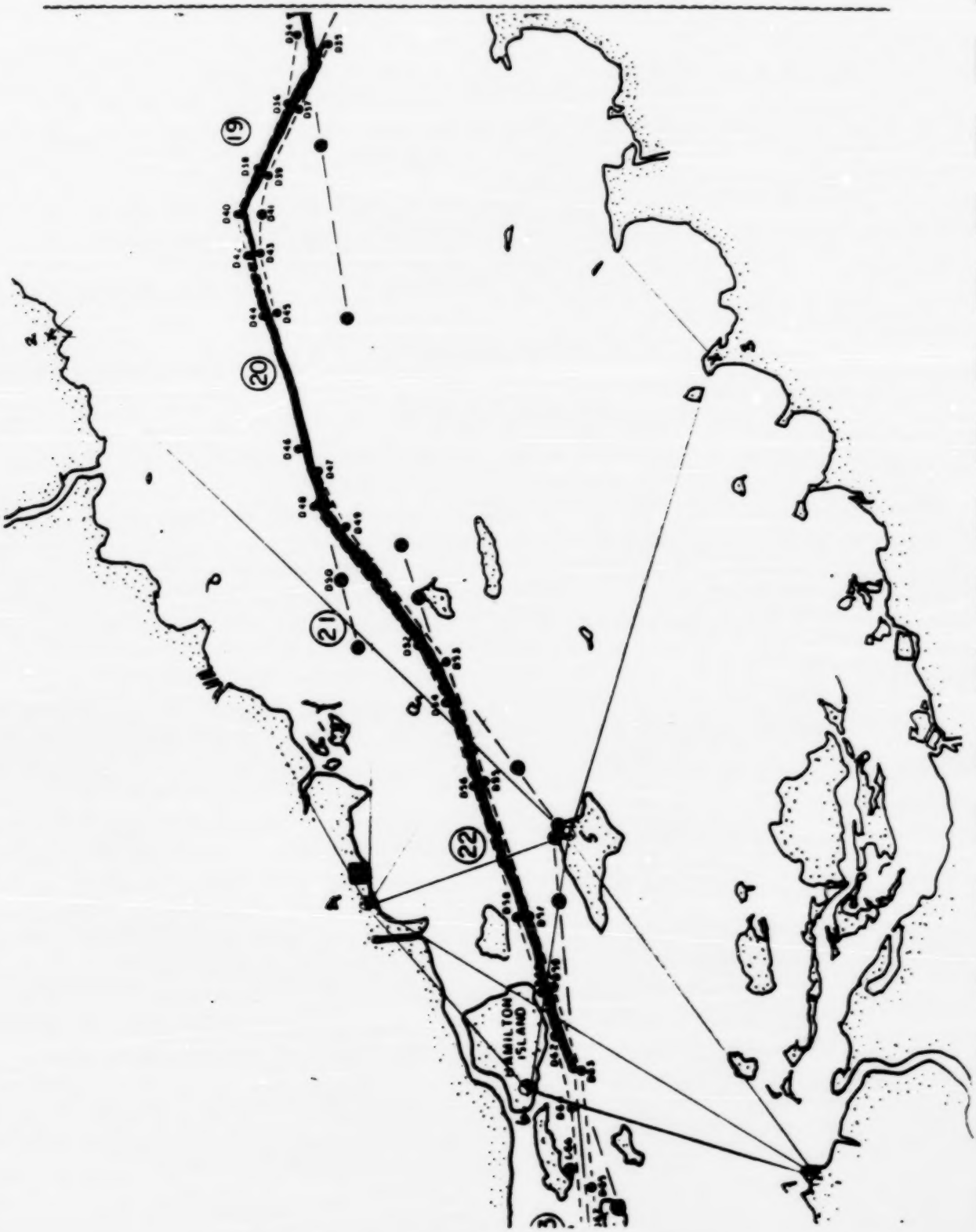


Figure 5-7 Reflectors for a Typical Stretch

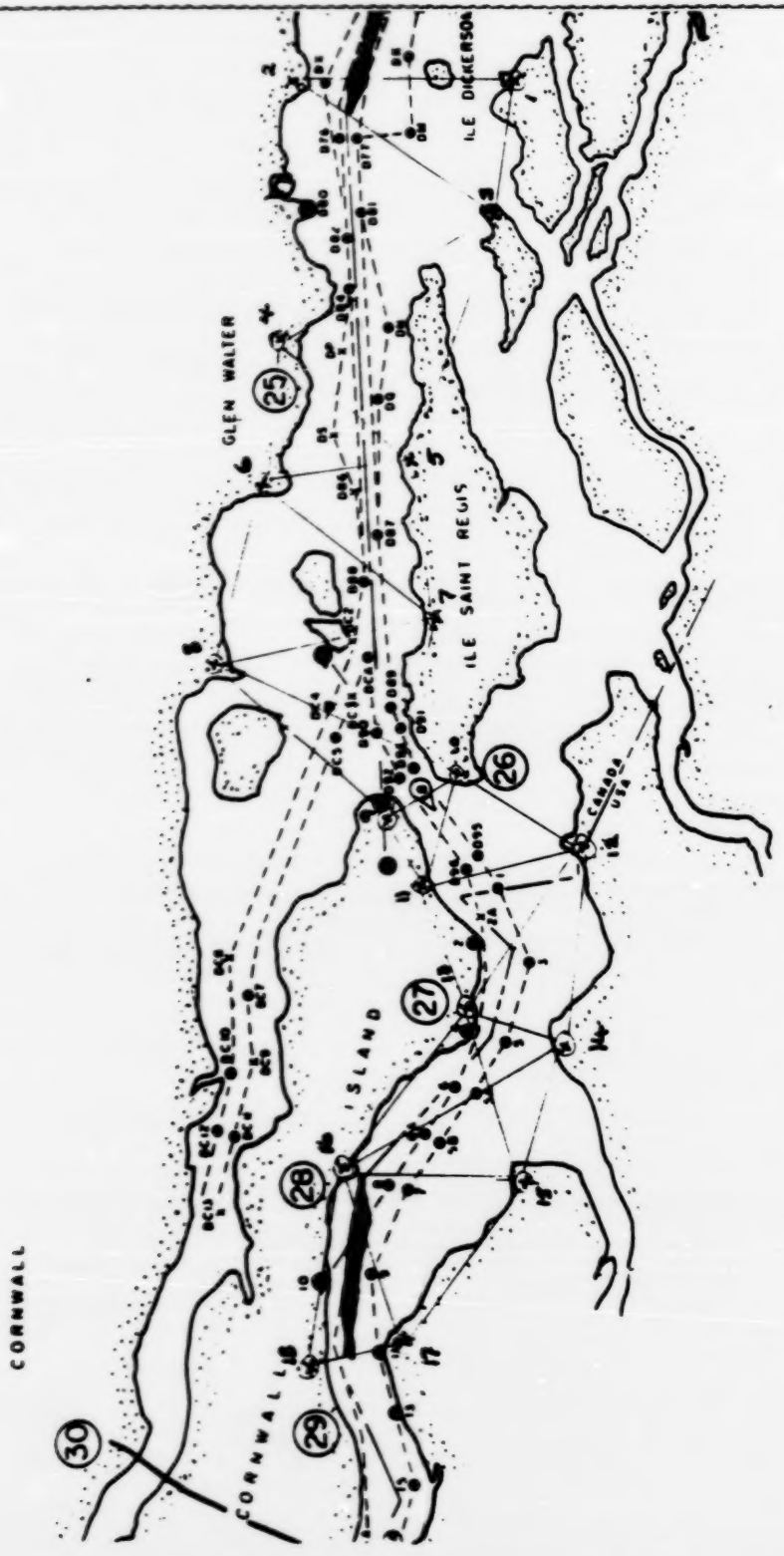


Figure 5-8 Reflectors for a Difficult Stretch

Table 5-3 Classification of the Reaches

Reach Numbers	Length (miles)	Type of Reach (T: Typical, D: Difficult)
1-5	31.2	T
6-14	15.7	D
15-24	26.6	T
25-33	18.9	D
34-41	13.5	T
42-62	36.3	D
63-70	15.0	T
71-76	10.0	D
77-83	24.0	T

Total length of typical reaches = 110.3 miles = 176.5 km

Total length of difficult reaches = 80.9 miles = 129.4 km

Length of stretch 1 (Reaches 20, 21, 22) = 6.1 miles = 9.76 km

Length of stretch 2 (Reaches 25, 26, 27 & 28) = 6.4 miles = 10.24 km

No. of reflectors for typical stretches = $\frac{6}{9.76}$ x 178.5 = 109

No. of reflectors for difficult stretches = $\frac{7}{10.24}$ x 129.4 = 215

The number of reflectors has been calculated by using a rough classification of the reaches and assuming that the reflectors are positioned along the shore line. The number can be reduced if the reflectors are positioned more inland from the shore line. However, they must be positioned at a greater height to avoid blockage due to terrain features and vegetation. This will require higher towers for mounting the reflectors. For example by using tall towers, the range of reflectors can be reduced to (6 x 305.9/9.76) or about 80 towers. (It should be noted that reflectors at long range will generally be required to be proportionately bigger in size compared to those operating at near range.)

The required size of the reflectors is computed from the radar range equation, for a typical ship's radar. This signal-to-noise ratio is given by

$$\frac{S}{N} = \frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 R^4 kTBFL_S}$$

where P_t = Peak Tx power = 10 kw = 40 dBw,
G_t = Antenna one-way gain = 26 dB,
λ = Operating wavelength = 0.032 m = -14.95 dB,
R = Range = 5 km = 36.99 dB,
k = Boltzman's constant = 1.28×10^{-23} = -228.6 dB,
T = Noise temperature = 270°K = 24.31 dB,
B = Rx bandwidth = 20 MHz = 73.01 dB,
F = Rx noise figure = 14 dB,
L_s = System losses = 3 dB, and
σ = radar cross section of the target.

For target detection in noisy environments, the required signal-to-noise ratio is a function of the required probability of detection (P_d), probability of false alarm (P_{fa}), type of target and the number of pulses integrated. With an antenna rotation speed of 30 rpm, antenna beam width of 1 degree and a pulse repetition frequency of 3000 Hz, the number of pulses available for integration is given by

$$n = \frac{\text{Beam Width}}{(360^\circ \times \text{RPM}/60)} \times \text{PRF} = \frac{3000}{180} = 16.$$

The required signal-to-noise ratio to detect a Swerling 3 type of target (non Rayleigh scatterer with slow fluctuation) with a P_d of 0.95 and P_{fa} of 10^{-6}, is approximately 10 dB.

For S/N = 10 dB, the required value of σ is equal to 14.56 dB or 28.58 m^2. The radar cross section of a trihedral reflector is given by $4\Pi a^4/3\lambda^2$, where 'a' is the length of the side of the reflector. For σ = 28.58 m^2, the reflector size is given by a = 0.3 m. An optimal orientation for the trihedral twist reflector is shown in Figure 5-9. The elevation and azimuth coverage of the reflector is about ±10 degrees. In order to cover the azimuth range of 120 degrees, a total of six reflectors must be used in a semi-circular configuration.

Multipath effects are minimized by setting up a second set of reflectors in a similar configuration, at a different height. The heights must be chosen such that for the nominal range of operation and height of ship's radar antenna, at least on least one set of reflectors are not coincident with the nulls produced due to multipath. The vertical lobe structure caused by the presence of a plane reflecting surface, as shown in Figure 5-10, comprises of maxima and minima, which are defined by:

$\frac{4h_a h_t}{\lambda R} = 2n + 1$ for the maxima, and

$$\frac{2h_a h_t}{\lambda R} = n \text{ for the minima,}$$

where n = 0,1,2,..., an integer,

h_a = height of the ship's antenna,

λ = wavelength of operation,

h_t = height of target, an

R = slant range to the target.

The distance between two adjacent nulls (or two adjacent maxima) is given by $\lambda R/2h_a$, which is tabulated for different values of h_a and h_t in Table 5-4. The lobes begin with a null at ground level. Considering a typical set of parameters with h_a equal to 15 m and range equal to 7.5 km, the reflector must be positioned at a height of 3 m so that it is at the position of the new lobe maximum point. If the range is further reduced by half to 1.875 km, the nulls would be 1 m apart and both the reflectors would be affected by nulls. Two possible solutions to this problem are to either introduce an extra set of reflectors at a different height or to make the reflectors large enough so that they cover a wider area of the lobe pattern.

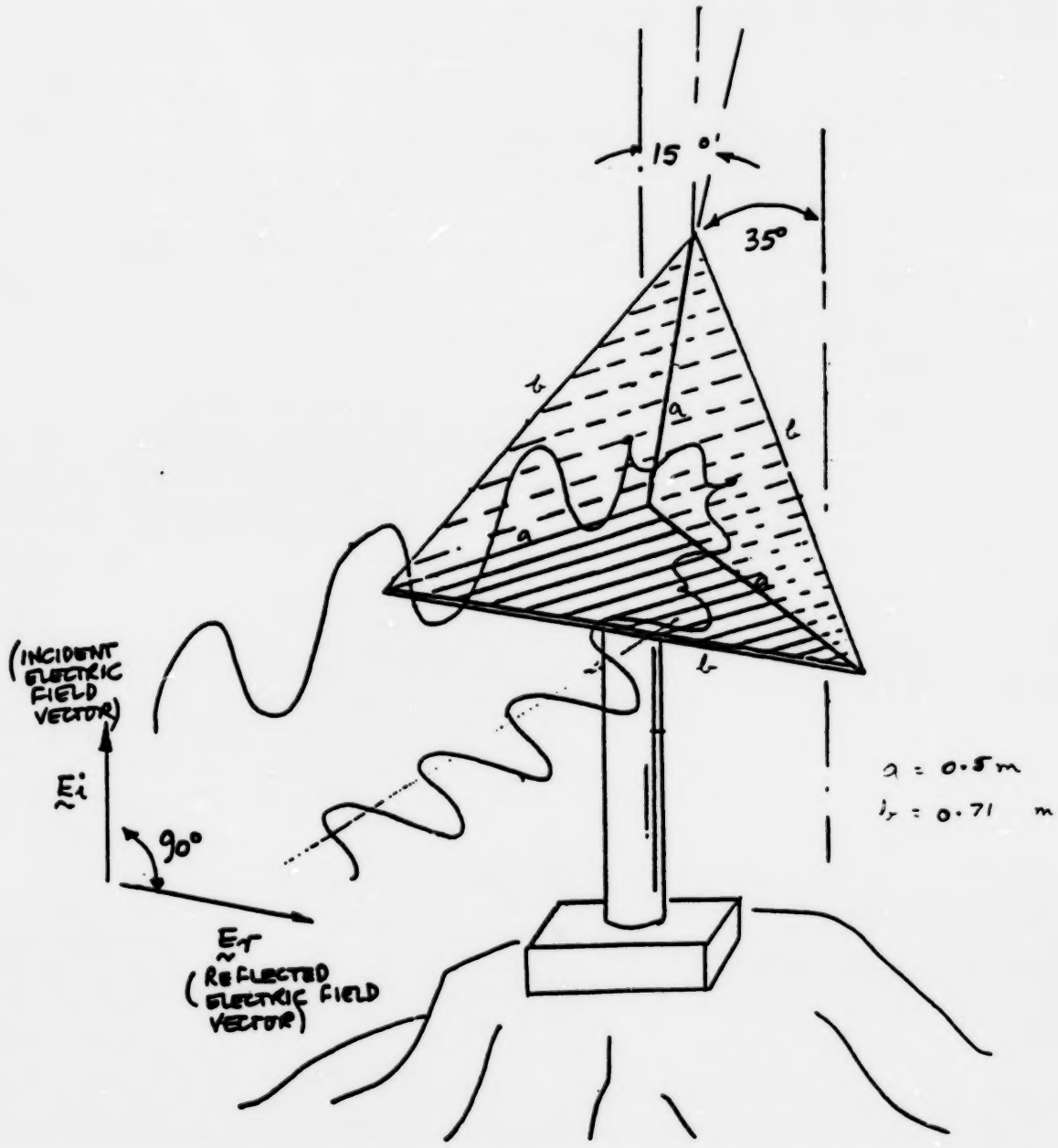
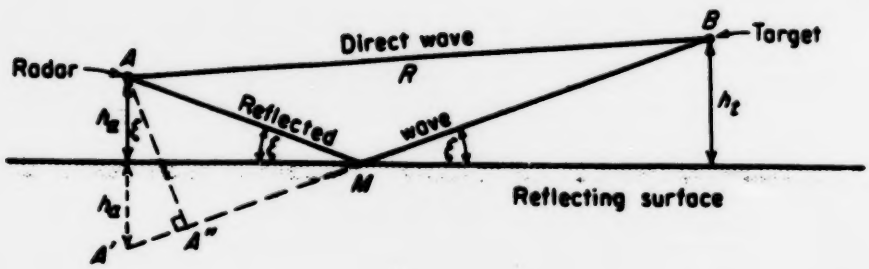


Figure 5-9 Optimally Oriented Trihedral Twist Grid Reflector



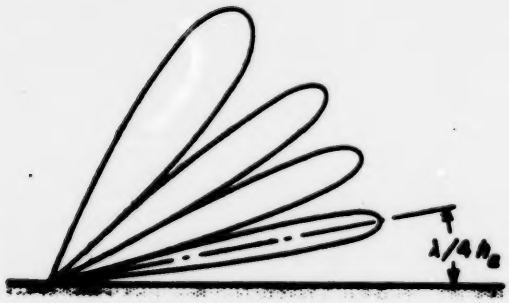


Figure 5-10 Multipath Propagation Over a Plane Reflecting Surface Causing Vertical Lobes

Table 5-4 Distance Between Two Adjacent Nulls or Two Adjacent Maxima ($\lambda R/2h_a$)

λ = 0.032 m

h_a = ship's antenna height

h_a	Distance Between Nulls (or maxima) in m					
(m)	R = 1 km	2 km	3 km	4 km	5 km	7.5 km
10	1.6	3.2	4.8	6.4	8.0	12.0
15	1.07	2.13	3.2	4.27	5.33	8.0
20	0.8	1.6	2.4	3.2	4.0	6.0
25	0.64	1.28	1.92	2.56	3.2	4.8

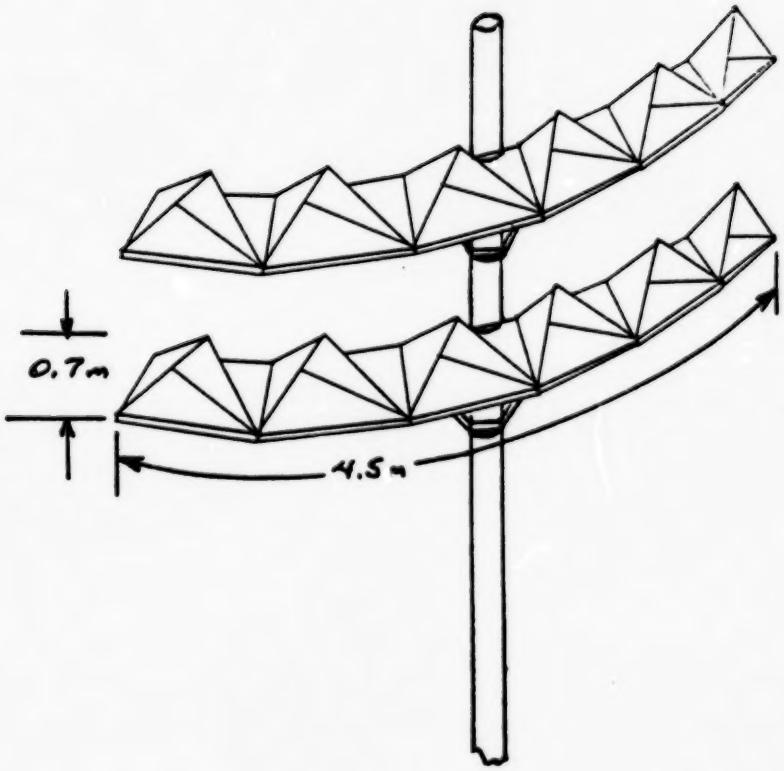
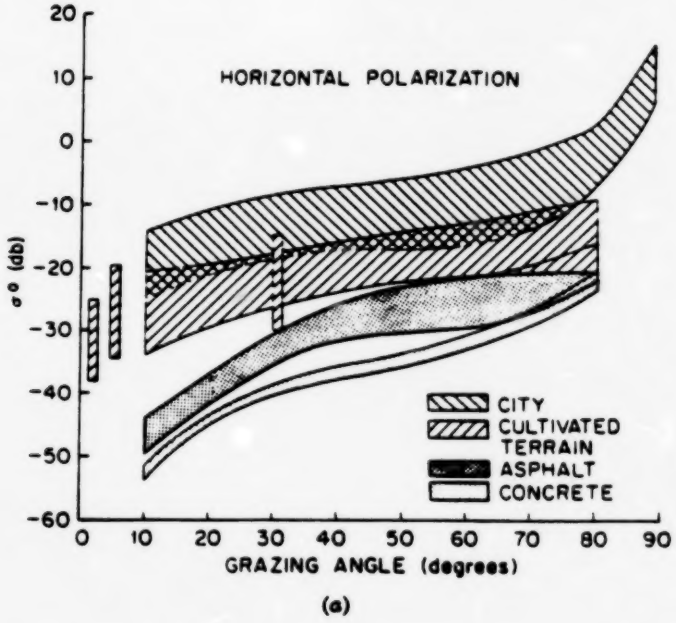


Figure 5-11 Proposed Configuration for Polarmetric Reflector Arrays



(a)

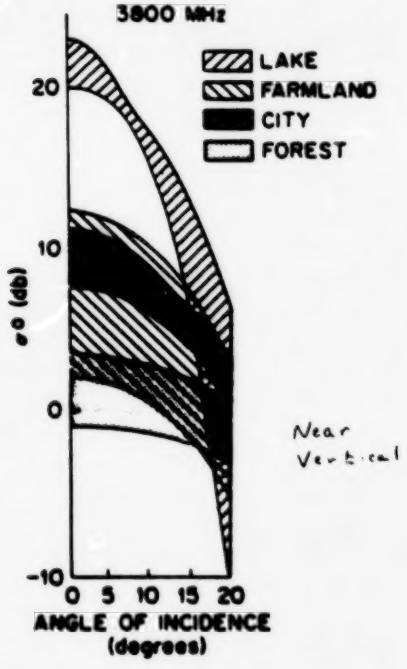


Figure 5-12 Typical plot of σ° versus grazing angle

For typical reaches with a maximum range of operation of 5 km, the side length of the reflector was computed as 0.3 m. For difficult reaches, where the maximum range is limited to about 2 km, the required side length is 0.12 m. Because the reflector size is small, a third row of reflectors may be added to the reflector array in order to reduce the effect of multipath. Alternatively, the size of reflectors may be increased (i.e. to 0.5 m) so that the front face of the reflectors covers the major portion of the interference lobe. The second option is preferred since it increases the radar cross section of targets for near range operation, where the clutter is often more severe due, for example, to a vertical cliff face. A suitable configuration for the polarimetric reflector arrays is shown in Figure 5-11.

The performance of the targets in clutter is dependent on the clutter cell cross section, the incidence angle and the reflectivity of the terrain. At a range (r) of the 5 km, for an azimuth beam width (θ) of 1.23° (0.0215 rad) and a radar pulse length of 50 nsec, (range resolution Δr of 7.5 m), the area of the clutter cell is approximately equal to $A = r\theta\ (\Delta r) = 5000 \times .0125 \times 7.5 = 805$ sq. m. The average return from a clutter cell is given by $\sigma = \sigma^\circ A$, Where σ° is the normalized radar cross section (RCS) of clutter. A typical plot of σ° versus grazing angle is shown in Figure 5-12 for different types of clutter. If the average value of land clutter is assumed as -20 dB, then σ will be equal to 8.05 sq. m., which is still lower than the RCS of the reflector (which equals 255.7 with a reflector side length of 0.5 m.

If the clutter is caused by vertical surfaces such as a rock cliff face with reflections at near normal incidence, the average value of clutter return will be approximately given by $\sigma = \sigma^\circ\ (r\theta \times \Delta h)$, where Δh is the height of the vertical surface. If Δh is assumed as 2 m, and σ° is equal to 0 dB at normal incidence, the value of σ would equal the RCS of the reflector (255.7 m^2) at a range of:

$$r = \frac{255.7}{\theta\ \Delta h\ \sigma^\circ} = \frac{255.7}{.0215 \times 2 \times 1} = 5.11 \text{ km}$$

For operation at 5 km, the value of σ° at which the average clutter equals the signal is given by:

$$\sigma^\circ = \frac{255.7}{r\ \theta\ \Delta h} = \frac{255.7}{5000 \times 0.0215 \times 2.0} = 0.1 \text{ dB}$$

This can be tolerated since polarization discrimination gives a signal-to-clutter ratio of 10 dB at this value of σ°, as assumed earlier.

5.3 RADAR TRANSPONDER

Radar transponders or (racons) can be used with the ship's radar as targets in place of passive reflectors. The transponders may be readily discriminated from ground clutter by using either special coding or frequency discrimination. Each racon may be programmed with a suitable code, which it transmits on the receipt of a radar pulse. Since the maximum radar PRF is typically 3200 for the short (50 nsec) pulse length, and the required range of operation is less than 10 km (equivalent to 67 μs), the remainder of the period available between pulses (about 245 μs) can be used for transmission of the code. By matching this code at the output of the radar receiver, the range and azimuth to the racon can be obtained.

In a system using the transponders code to discriminate it from the background clutter, no modifications need to be done to the radar system. The raw video output of the radar receiver is digitized and passed on to a decoder, which identifies the code transmitted by a racon by pattern matching. Figure 5-13 shows the block diagram of a system using coded pulse detection of shore-based racons.

An alternative method based on frequency discrimination can be utilized instead. With this technique, the racon is programmed to transmit a signal slightly offset from the interrogating frequency (radar transmit frequency). The radar receiver is then determined to receive this offset frequency. This technique causes the racons to "stand-out" from surrounding clutter, since no clutter will appear at the offset frequency.

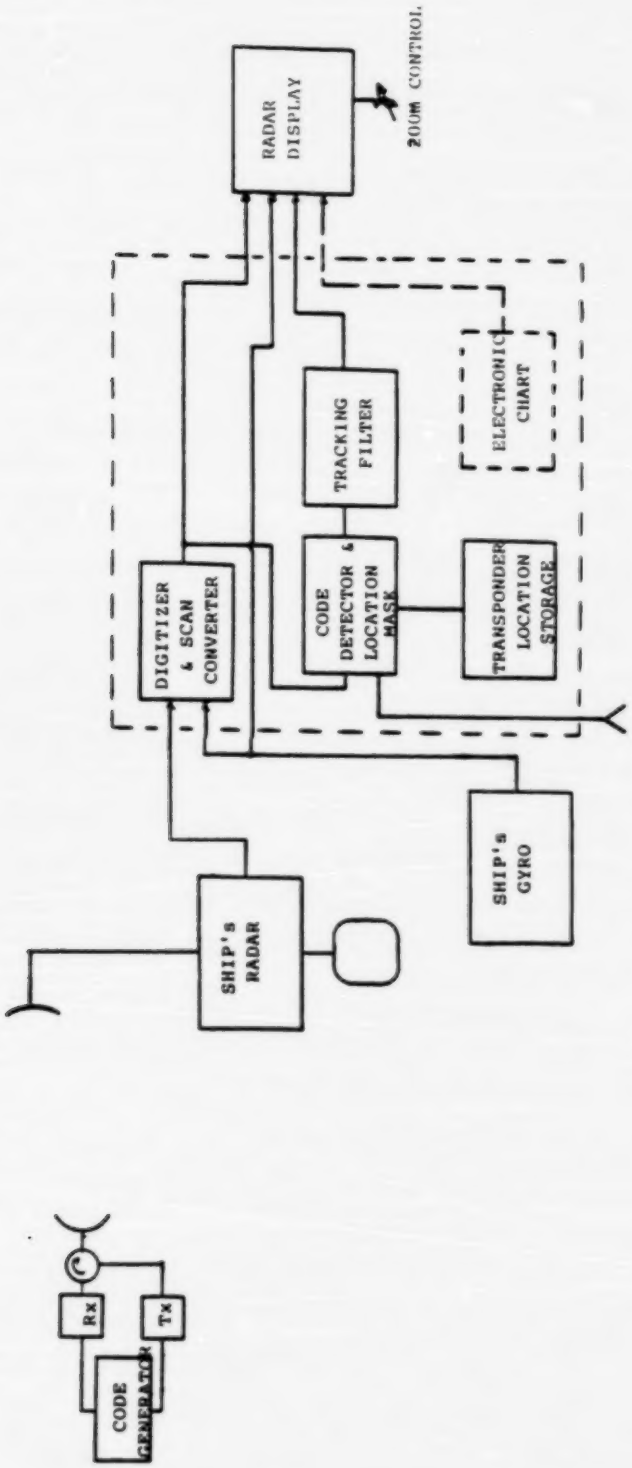


Figure 5-13 Radar Transponder System Block Diagram

A block diagram of the alternative frequency discrimination approach is shown in Figure 5-14, where alternate transmit pulses are used, the first for normal radar display the second for receiving the offset frequency. On alternate pulses the receiver is detuned to receive the offset frequency that is transmitted by the racon. In order to avoid interference with normal radar operation, only alternate pulses are processed by the radar. Since the radar display receives normal video for half the number of pulses, it will produce an image slightly dimmer compared to normal operation. However, the radar will display the transponder with the alternate pulses. Since this scheme alters the performance of the display, which may not be tolerated by the master of the ship, a third alternative would be to use a second radar receiver connected in parallel to process the offtune return signal from the racon. This second receiver would be permanently tuned to the offset frequency. A system implementing the third option is shown in Figure 5-15. The output of the second receiver is used to locate the transponders and subsequently to find the location of the ship. The output of the normal radar receiver is used to produce the radar image overlay on top of the graphic display.

The operation of a system using transponders requires the detection of the ship's interrogation pulse by the transponder in the forward path as well as the detection of the beacon signal received at the ship's radar receiver in the return path. The signal received at the beacon in the forward path is given by the equation.

$$P_{ri} = \frac{P_t G_t G_b \lambda^2}{(4\Pi)^2 R^2 L_f},$$

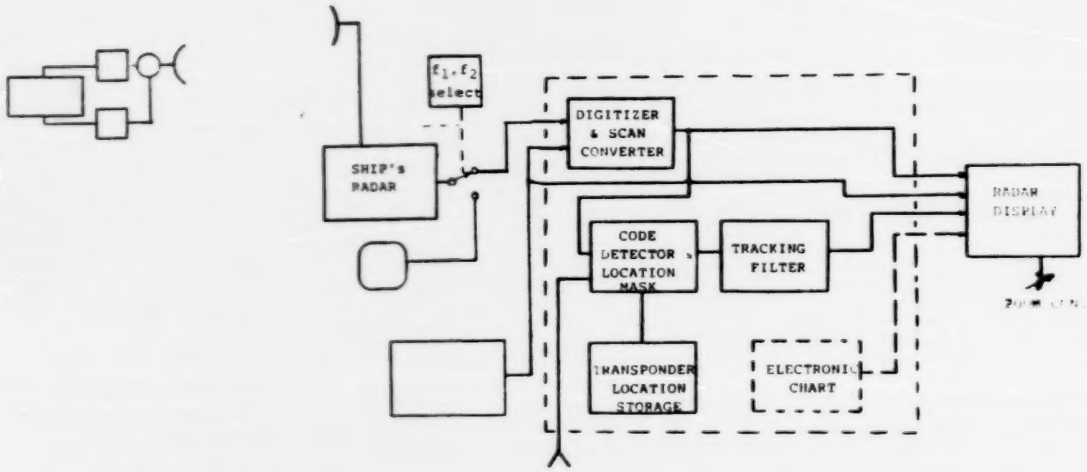


Figure 5-14 Transponder, Alternate Configuration

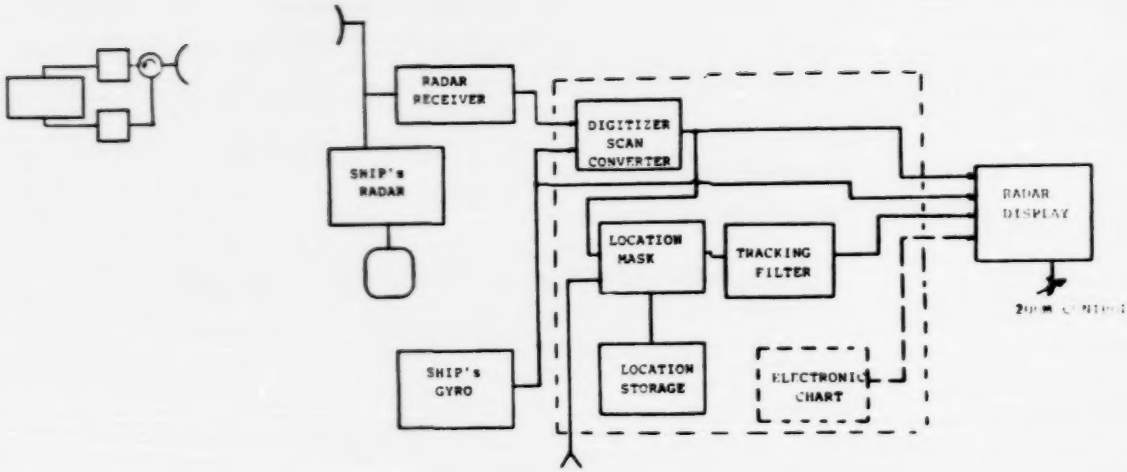


Figure 5-15 Transponder, Alternate Configuration #2

where P_t = Transmitted peak power = 10 kW = 40 dBw
G_t = Gain of the ship's antenna = 26 dB
G_b = Transponder antenna gain
= 0 dB for an omni antenna
λ = Operating wavelength = 0.032 m = -14.95 dB
R = Range = 5 km = 36.99 dB, and
L_f = System Losses in the forward path = 3 dB.

For an operating range of 5 km, the minimum required sensitivity of the beacon receiver is given by P_{r1} = -62.9 dBw =-32.9 dBm. This is easily achievable in the beacon receiver.

For the return path, the performance is specified by the level of the signal received by the ship's radar from the beacon, given by

$$P_{r2} = \frac{P_b G_b G_t \lambda^2}{(4\pi)^2 R^2 L_r}$$

where P_b = Beacon peak power
G_b = Gain of the beacon antenna, and
L_r = System losses in the return path.

The noise level in the receiver is given by

N = KTBF,

where K = Boltzmann's constant = 1.38×10^{-23} = -228.60 dB
T = System noise temperature = 270 = 24.31 dB
B = System bandwidth = 20 MHz = 73.01 dB, and
F = Receiver noise figure = 14 dB
$\therefore$ = N = -117.28 dBw = -87.28 dBm.

For a receiver sensitivity P_{r2} of -104 dBw (-74 dBm), L_r equals 3 dB, G_L is zero, R equals 5 km, the required peak beacon power P_b is 22.9 dBm or 193.2 mw. This provides a signal to noise ratio of about 13 dB.

In the forward path, there is a possibility of the racon being triggered through the side lobes of the transmit antenna. With the sidelobes 20 to 25 dB down with respect to the main lobe, a racon at near range may be triggered continuously if the sidelobe signal level is higher than the sensitivity of the racon receiver. This is usually avoided by using a sidelobe suppression (SLS) feature in the racon receiver.

If the coded transponder technique is chosen to avoid modifications to the ships radar, it is possible the clutter surrounding the transponder would be so high as to suppress the transponder signal and prevent reception and identification. This is avoided by delaying the transponder response by, for example, 100 usec, so that the clutter is reduced below noise. This increases the complexity of the transponder.

If the transponder should be simultaneously interrogated by more than one ships (usually on a different frequency), the transponder must reply to both transmissions or tracking will be lost. The transponder must not be "blocked" for more than about 10% of the repetition period to allow several ships to reliably interrogate the same transponder.

As for the polarimetric radar, multipath is also a potential problem. The transponder receiver antenna must either be sufficiently large to avoid being in the pattern null, or two or more antennas using spatial diversity must be combined to avoid the pattern null.

The cost of a typical radar transponder is about $30 K. If the total number required is assumed as equal to that for the polarimetric radar (i.e., 314 transponders), the total cost of transponders would be about $8.8 million. Power, either AC mains, battery, thermoelectric generator or solar cells is required for operation. Additional costs for shore installations include land acquisition costs, costs for towers, installation costs, plus periodic maintenance costs for the transponders as well as the batteries.

The shipborne equipment includes the location system, tracking system and the display, apart from additions or modifications to the ship's radar. Therefore a radar transponder system will be considerably more expensive than the Clutter Correlator.

5.4 RADIO RANGING SYSTEM

A microwave ranging system, being a line-of-sight system, requires a similar number of shore sites to that needed for radar polarimetric reflectors or radar transponders. A typical microwave transponder costs around $25 K. As in the case of radar transponders, the total costs for shore installations must also include power system costs, site costs, tower costs, installation costs plus operating costs which must include periodic maintenance. The cost of the shipborne equipment must include the cost of an interrogator and location system (about $25 K), as well as the cost of a tracking system and display.

In the case of the UHF ranging system, because of increased in operating range, fewer number of transponders can be used. A preliminary estimate suggests that one site per 15 km would be sufficient, thereby significantly reducing the costs of such a system. Since this system is still more expensive then a Clutter Mapper radar approach it was not considered further.

5.5 DIFFERENTIAL GPS

The cost of GPS receivers have been decreasing rapidly in recent years, because of the use of modern technology and competition among manufacturers. The cost of a stand-alone receiver is currently about $50 K and is bound to reduce in the future, because of navigational applications in land, sea and air. By using differential receivers, it is quite probable that GPS will become a viable system in the future. The trends in system design of the GPS receiver are still in the evolutionary stage, for example, the more recent generation of GPS receivers use techniques to simultaneously lock on to all the satellites in view instead of multiplexing, as was done earlier.

The cost of a GPS system must include:

i) A ship based GPS receiver with antenna
ii) Two shore based differential GPS receivers
iii) A dedicated, high reliability data link to all users (possibly UHF)
iv) A differential correction processor, a gyro interface, a tracking system and a display are also required.

The GPS computed position should ideally be integrated into a digital radar display so the ship's captain can observe other ships as well as observe his own position. A block diagram of such a GPS system is shown in Figure 5-16.

There are two specific long term concerns about the GPS approach which must be resolved prior to implementation. These are:

a) Inadequate satellite health message response time
b) Possible outages

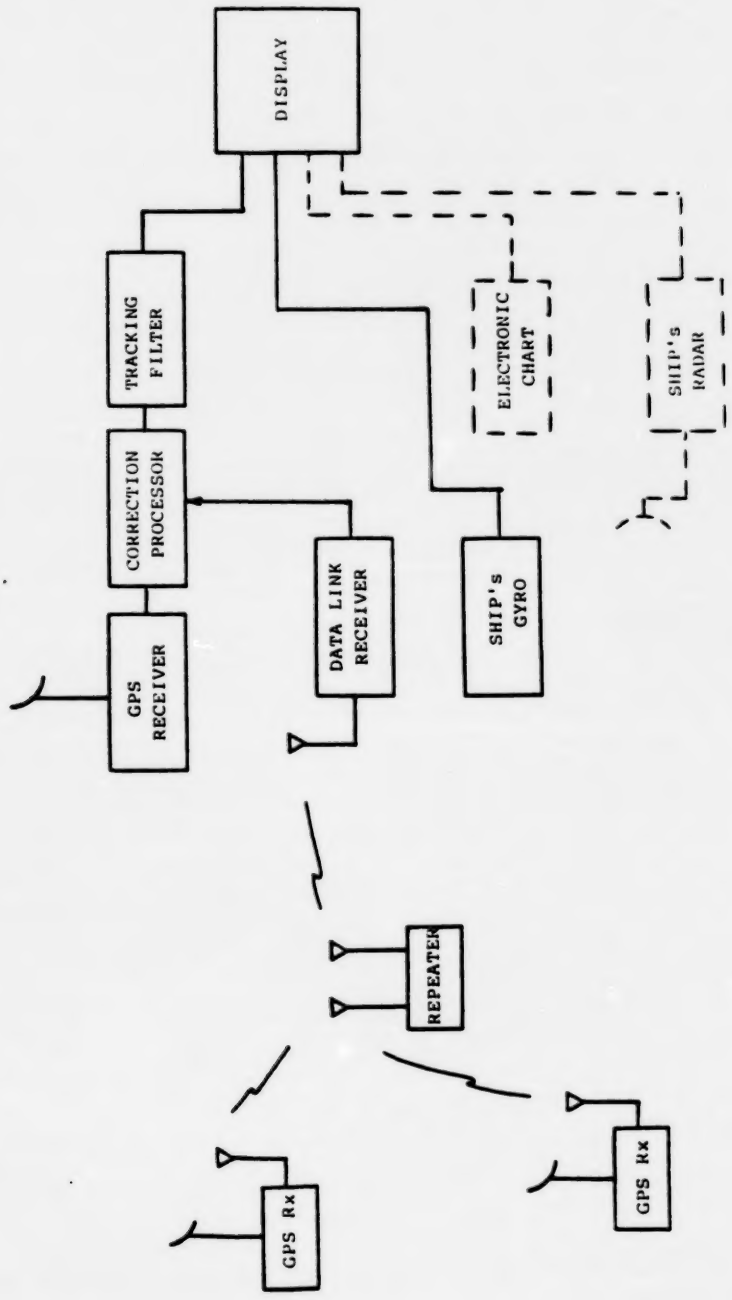


Figure 5-16 Differential GPS System Block Diagram

The first problem is quite serious. It is proposed that an operational satellite message indicating "poor" health or inadequate performance will be sent 12 seconds after the fault is detected. This would likely present an inadequate warning time to a ships captain.

An insufficient number of satellites might be available for continuous coverage. Outages (i.e.: reduced accuracy periods) of up to 20 minutes have been predicted. While this is not catastropic it would be very annoying, and could substantially reduce the cost benefit.

5.6 PRELIMINARY COST-BENEFIT ANALYSIS

Both relative costs, and the cost of the selected system are estimated.

5.6.1 RELATIVE COST ESTIMATE

The relative cost of each of the 4 systems was estimated based on the requirements data tabulated in Table 5-5 and the following assumptions:

i) Tracking and display subsystems are identical for each approach.

ii) A gyro is included on ship and is needed for all approaches.

iii) Each ship is already equipped with an X-band radar (50 nsec pulse width) and antenna.

iv) The number of shore-based sites is based on targets mounted on short masts near shoreline. (This number could be reduced at expense of using taller towers further from shore).

Based on the assumption that shore based transponders with power supplies are signficantly more expensive than passive reflectors when maintenance costs are included, Radar Transponders and Radio Ranging Systems

Table 5-5 Requirements Unique to Each Approach

APPROACH	SHIP-BASED EQUIPMENT	SHORE-BASED EQUIPMENT	NOTES
Correlation Radar	- Ships Radar - Correlator and Storage Unit	None	Stored Radar Image Needed
Polarimetric Radar	- Ship's Radar, modified with extra receiver - Modified Radar Antenna	- 314 passive polarimetric reflectors	
Radar Transponder	- Ship's Radar - Decoder Subsystem	- 314 transponders with power supply	
Radio Ranging System	- Interrogator Unit	- 314 transponders with power supply	
Differential GPS	- GPS Receiver - Differential data receiver	- 2 differential sites - Dedicated radio link	Integration with ships radar is optional

can be excluded on the basis of cost.

The polarimetric radar requires construction and installation of several hundred shore based transponders. Cost are estimated as follows:

Dual Array - $2K to $6K (in quantity)
Site Purchase - 0 to $30 K
Mast and installation - $5 K

Modifying a ships radar and antenna could cost between $10 K and $40 K depending on the number of different radars and antennas currently in existance which require modification.

Since the Image Correlation Radar requires no shore based equipment and preparation of a reference radar image storage file is estimated to cost less then $1 M, the Polarimetric Radar is significantly more costly.

The Differential GPS cannot be costed because the system is not yet operational. However it is likely to be more expensive than the Image Correlation Radar. Receiver/antenna costs should drop to the $2-8K region depending on demand. The installation and maintenance for two receiving sites and a dedicated data link was not estimated, however it should not exceed a few million dollars over a 10 year period.

5.6.2 SELECTED SYSTEM COST ESTIMATE

The Image Correlation (or Clutter Mapper) Radar is considered significantly less expensive than the alternatives, therefore more information on expected costs and benefits are provided.

5.6.2.1 Benefits

Further information on "lost time" costs should be sought in the user community, however based on rough verbal estimates, operating costs of about $15 K per day have been estimated for a ship waiting at anchor. Lost profit is even harder to estimate due to competitiveness and extreme variability from year to year, however $5 K per day profit seems like a reasonable guess. Then, based on an extended 290 day Seaway season and a DMA conclusion reached in 1981 that 6% of time is lost due to fog and ice, 17 days per ship may be persumed to be "lost".

Thus a per ship loss of between $250 K and $340 K per year might be reasonable. It is considered beyond the scope of this study to confirm these figures.

5.6.2.2 Costs

Costs can be conveniently divided into fixed, variable, and non-recurring.

Fixed costs include purchase and installation of a Clutter Mapper subsystem, to be interfaced to an existing ships radar and gyro. The cost will strongly depend on the quantities involved. Since any number of ships might decide to take advantage of the technology, from one to one hundred, a unit suitably packaged for the marine environment should cost about $60-90 K in quantities of 20, with lower costs for large quantities. This estimated cost may be expected to fall due to the current dropping costs for fast digital processors, semiconductor memory, and compact disc memory units.

Variable costs include maintenance and upgrading of reference radar images. Maintenance should be minimal since most of the system is digital requiring little care. The radar performance is crucial, therefore the subsystem should include Built-In Test Equipment (BITE) to continuously automatically test the ship's radar performance, and notify the operator if radar maintenance is needed.

Upgrading of radar images could be done using floppy discs as the storage transfer medium, or alternatively new compact discs could be plugged into the system.

Non-recurring costs include:

i) Reference Image Data Gathering
ii) Software Development

The gathering of reference radar image data should be accomplished such that the results are applicable to any ship's radar meeting the performance requirements. This means that the ship should be "clean" with minimal shadowing and on-board reflections. The equipment used to generate the images at each reference point could be a modified version of the Clutter Mapper Subsystem with the capability of storing the data on a compact (laser) disc. A radio ranging system will have to be leased and surveyed-in to provide the necessary accuracy for each reference point position. (i.e. must be more accurate then the radar itself). Ideally the radar image should be capable of being overlaid with key information from a chart, (i.e.: an electronic chart) to make the system easier to use.

Once the initial reference images were made, the only required action would be upgrading for large new man-made structures, possibly once per year or less. The associated optional electronic charts could be updated more often as required.

It is estimated the Data Gathering task would cost 0.5 - $1 M using this approach.

McGill University have prepared a software package which has proven adequate for 10 meter accuracy on a single ship. This software would have to be upgraded and modified for use under varying weather conditions, for use by differing ships with different radars, and to be capable of applying suitable "masks" for the areas of water applicable to the Seaway. A tracking algorithm would have to be prepared compatible with the typical dynamic operating characteristics of ships using the Seaway.

Preferably this software should be ROM-based firmware or hard disk with magtape back-up, to assure reliable performance.

The non-recurring cost of preparing or modifying existing software is estimated as $0.1 to 0.5 Million depending on the information currently available on effects of the environment (particularly rain) and the data available on the differences between various ships radars.

5.6.2.3 COST/BENEFITS

The cost of the system is estimated to be $60-90 K fixed, with minimal maintenance, and $0.6 to $1.5 M non-recurring. Based on purchase by 20 ships and 10 year payback, the average estimated cost is $60-90 K initial plus $3K to $8K per year per ship.

Based on the estimated benefit of from $250-340K per ship per year, it is clear the benefit/cost ratio is very high and potential users should be sufficiently encouraged to purchase the system purely on the basis of financial benefit.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This study has concluded that there are five techniques that are technically suitable for navigating a ship through the St. Lawrence Seaway with the required accuracy. However, of these techniques, one has been identified as the most cost effective. The key advantages and disadvantages of each technique are presented below:

i) Differential GPS - This system, assuming GPS does become operational (probably by 1990 or 1991), can provide good accuracy and, due to the benefits of quantity production, the receiver should be reasonably low cost. The system however, will require two shore based receiving stations and a dedicated data link which makes it expensive. Two potential problems which must be solved by the GPS managers are that the availability may not be 100% and "bad satellite" messages are delayed by 12 seconds or possibly longer. Unless these problems are solved this technique is quite risky, particularly in fog. This system cannot be recommended due to the large number of unknowns at this time.

ii) Microwave Ranging Transponders - This system can provide very good accuracy, however, due to the requirement for a large number (up to 314) of powered shore based transponders, it is quite expensive. This system cannot be recommended because of the cost of installing and maintaining the shore based stations.

iii) Radar Transponders - This system utilizes a standard ship's on-board radar and is therefore lower cost than the Microwave Transponder. However, the requirement for a large number (up to 314) of powered shore based transponders makes it expensive. This system also cannot be recommended because of installation and maintenance costs.

iv) Polarimetric Radar - This system offers the advantage that ship's radar is used and the shore based transponders do not require any power. However, a large number (up to 314) of shore based reflectors have to be installed and the ship's radar must be modified, which makes it more expensive than an Image Correlation Radar system. This higher cost prevents this system from being recommended for this application, however for those applications where high tides or moving ice which cannot easily be masked are a problem, this system offers a viable alternative.

v) Image Correlation Radar - This system also utilizes a standard ship's radar but requires no shore based installations, therefore resulting in a lower cost. The system does require, however, that a number of digitized reference radar images be collected and stored on a disk or similar storage medium. This system is fundamentally capable of meeting the accuracy requirements, is lowest in cost, and therefore is recommended for further development.

Having recommended that a Image Correlation Radar (or Clutter Mapper) be considered best suited for this application, it is appropriate to suggest how this system, which is currently in the research phase, might be developed and proven to the user community.

McGill University have conducted sufficient research to show that the concept is fundamentally sound. This fact, together with current technology improvements, particularly in the areas of lower cost computational power (array processors) and digital storage devices (compact or laser disk), make tne development of this technique into a world-wide accepted approach most desireable.

The technique has been demonstrated on a ship deployed in Halifax harbor. While the accuracy achieved was insufficient for the current application, there is no fundamental reason why the necessary accuracy improvement cannot be achieved by applying well-known hardware and software refinements.

The recommended approach is to demonstrate, preferably on a ship in the St. Lawrence Seaway, that the accuracy is achievable utilizing a standard ship's radar. The following basic concepts will certainly initially and/or ultimately have to be proven before a ship's captain will totally rely on the system to guide his ship through the Seaway in dense fog:

i) the necessary accuracy is achievable reliably without major modification to the ship's radar,

ii) the required processing power can be realized in a reasonably sized package suitable for a ship's environment at a reasonable price,

iii) the reference images required for the Seaway can be stored on a small number (preferably one or two) compact disks,

iv) the technique will work quite satisfactorily with undesirable areas of the radar image masked off,

v) a tracking algorithm, with time constants selected appropriate to a Seaway ship, is defined and proven,

vi) reference images produced by one ship's radar can be used by another radar having similar characteristics,

vii) weather effects, such as wind, rain, fog, snow, etc., do not cause the image to deteriorate to a level sufficient to reduce accuracy,

ix) deterioration caused by any malfunction in the ship's radar or gyroscope is detected reliably within 4 seconds or less,

x) the digitized radar display, (showing all objects including other ships), with the current ship's position and historical positional images superimposed, can be easily used by the ship's captain or pilot to steer the ship without benefit of buoys, etc.,

xi) it is preferable that an electronic chart be readily integratable into the digitized radar display, to outline land areas, man made objects, and navigational aids, thereby simplifying the decision making process.

There are several ways to demonstrate all of these concepts, one particularly suitable approach might be to proceed as follows:

i) Choose a ship which regularly navigates the Montreal to Kingston portion of the Seaway and, add a prototype Clutter Mapper to the ship's radar.

ii) For a typical section of the Seaway, for example reaches 19 to 29 (running from Lake St. Francis to Cornwall), and using a properly calibrated ship's radar, obtain a series of reference images and store them in a digital memory. Microwave transponders can be leased and placed at suitable locations on the shore so that the precise location of the centre of each reference image can be determined.

iii) Produce a prototype model Clutter Mapper system suitable for a ship environment (but not necessarily packaged in a optimum manner), incorporating a radar mask, a tracking algorithm, and a digital radar display with a superimposed ship's image.

iv) Integrate the Clutter Mapper, the ship's radar and the ships gyro, insuring the radar is calibrated properly.

v) Operate the system several times during the year as the ship passes through the area, watching for abnormalities of behaviour. Since heavy rain is of particular concern, operation under this condition should be an objective. If possible, an electronic chart should be added to make the system more operator friendly.

vi) Once confidence is achieved, block the view of the outdoor conditions from a second operator, and compare the "real operator's" performance with the instructions from the obscured operator.

If possible, operate the ship after the buoys are removed. (For record purposes a video tape recorder (VCR) might be used to allow review of the digital radar performance in slow motion at a later date.

vii) The final step involves using the radar image obtained using one ship to steer a second ship through the same area.

viii) Having proven the soundness of the technique, the entire St. Lawrence portion of the Seaway could be "mapped". There are significant advantages to having this task performed by a government agency, such as the Canadian Hydrographic Service (CHS), since the images should be available to any and all users, local or international.

These steps, while somewhat arbitrary, will assure development of a fundamentally sound solution to a problem which is both Canadian and international in character, thereby improving the competitive advantage of marine transport .

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APPENDIX A

DESCRIPTION OF SEAWAY REACHES

GEOMETRIC DESCRIPTION OF SEAWAY REACHES
PILOTING REQUIREMENTS

Reach Description	Reach Number	Upbound Channel Bearing (°T)	+ = R - = L Turns	Channel Length Stat.Miles	Channel Width (ft)	Channel Width (m)	Cross Track Requirements (± from C.L.)	Nav Aids Adequate
CIP2 - Entrance to Lake St.Louis	1	This section is ± 20 miles long. It consists of a confined waterway having two locks. It is considered that nav. aids (lighting, etc) in this reach are adequate and no other system will be required.						
Entrance to Lake St. Louis	2	266	- 42	2.3	600	182		
	3	224	+17.5	4.7	600	182		
	4	241.5	- 23.5	3.0	800	243		
	5	218		1.2	1400	426		
Beauharnois Locks	6	This section is 2.2 miles long. It consists of two locks and an intermediate pool. It is considered that nav. aids in this area are adequate and no other system will be required. Channel bearing is 209.3°.						
Beauharnois Canal	7	208.5	+17.5	2.6	600	182		
	8	226	+11	2.5	600	182		
	9	237	0	0.4	600	182		
St.Louis Bridge	10	237	+11.5	0	180	54		
	11	248.5	+21.5	1.5	600	182		
	12	270.0	+17.5	4.1	600	182		
Valleyfield Bridge	13	287.5	0	0	180	54		
	14	287.5	- 24	2.4	600	182		

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PILOTING REQUIREMENTS

Reach Description	Reach Number	Upbound Channel Bearing (°T)	+ = R - = L Turns	Channel Length Stat.Miles	Channel Width (ft)	(m)	Cross Track Requirements (± from C.L.)	Nav Aids Adequate
Valleyfield Bridge	15	263.5		4.4	450	137		
			- 21					
Lake St.Francis	16	242.5		2.8	1200	365		
			- 33.5					
	17	209		2.2	900	274		
			+25.5					
	18	234.5		6.6	650	198		
			+32					
	19	266.5		1.2	480	146		
			-37.5					
Lancaster Bar	20	229		2.2	450	137		
			-21.5					
	21	207.5		1.4	450	137		
			+19.5					
	22	226		2.5	450	137		
			+13.5					
	23	239.5		2.2	450	137		
			+23.5					
	24	263		1.1	450	137		
			-22					
Glengarry Anchorage	25	241		3.5	450	137		
			-32					
CWL & St.Regis Island	26	209		.9	450	137		
			+27					
Turn CWL Island	27	236		1	700	213		
			+42					
	28	278		1	450	137		
			-44					
Turn Seaway Int. Bridge	29	234		2	1000	304		
			+33					
	30	267		0	600	182		
			0					
	31	267		0.75	700	213		

GEOMETRIC DESCRIPTION OF SEAWAY REACHES
PILOTING REQUIREMENTS

Reach Description	Reach Number	Upbound Channel Bearing (°T)	+ = R - = L Turns	Channel Length Stat.Miles	Channel Width (ft)	Channel Width (m)	Cross Track Requirements (± from C.L.)	Nav Aids Adequate
Snell & Eisenhower Locks	32	This section is 7.75 miles long. It consists of two locks and an intermediate pool. It is considered that nav. aids in this area are adequate and no other system will be required.						
Wiley-Dondero Canal	33	257		2	450	137		
			0					
	34	257		2.5	600	182		
			-24					
Cat Island Shoal	35	233		1	610	185		
			+15.5					
Morrisburg Section	36	248.5		3	850	259		
			+13.5					
	37	262		1	850	259		
			-29					
	38	233		1	730	222		
			+22					
	39	255		1	700	213		
			-35					
	40	220		2	900	274		
			+17.5					
	41	237.5		2	600	182		
			+17.5					
	42	255		2	600	182		
			-18					
	43	237		1	600	182		
			-10					
	44	227		1	750	228		
			+21					
	45	248		.75	700	213		
			-6.5					
	46	241.5		1.25	700	213		
			-35.5					
	47	206		.5	500	152		

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Reach Description	Reach Number	Upbound Channel Bearing (°T)	+ = R - = L Turns	Channel Length Stat.Miles	Channel Width (ft)	(m)	Cross Track Requirements (± from C.L.)	Nav Aids Adequate
Iroquois Lock	48	This Section is about 1.1 miles long. It consists of one lock. It is considered that nav. aids in this area are adequate and no other system will be required. Channel bearing is 206°						
	49	206	+21	.7	700	213		
	50	227	+9.5	3.5	600	182		
	51	236.5	-15	2	600	182		
	52	221.5	+16.5	1.5	600	182		
	53	238	0	1.5	600	182		
Ogdensburg/Prescott Bridge	54	238	-18	0	750	228		
	55	220	+18	2.25	630	192		
	56	238	-15	1.75	1000	304		
	57	223	+8	7	1000	304		
	58	231	-8	3	1000	304		
McNair Island	59	223	+10	1.75	550	167		
Skeleton Island	60	233	+4	.75	500	152		
Smith Island	61	236	-14	1	400	121		
Brockville Narrows	62	222	-5	2	400	121		
	63	217	+23	2	650	198		

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PILOTING REQUIREMENTS

Reach Description	Reach Number	Upbound Channel Bearing (°T)	+ = R - = L Turns	Channel Length Stat. Miles	Channel Width (ft)	Channel Width (m)	Cross Track Requirements (± from C.L.)	Nav Aids Adequate
Whaleback Shoal	64	194		2.5	610	185		
			+24					
	65	218		1.4	610	185		
			-2					
Superior Shoal	66	216		3.1	610	185		
			-7					
	67	209		1.9	610	185		
			-2					
Sister Island	68	207		1.1	610	185		
			+18					
	69	225		1.2	610	185		
			+3					
Whiskey Island Shoal	70	228		1.8	610	185		
			-10					
American Narrows	71	218		2	600	182		
			-4					
	72	214		1	400	121		
			+5					
	73	219		2	450	137		
			+16					
	74	235		2.5	450	137		
			0					
1000 Island Bridge	75	235		0	450	137		
			-4					
	76	231		2.5	450	137		
			+8					
	77	239		2.5	550	167		
			-11					
	78	228		1	600	182		
			+18					
	79	246		7.5	730	222		
			+17					
	80	263		4	800+	243+		
			-69.5					

GEOMETRIC DESCRIPTION OF SEAWAY REACHES
PILOTING REQUIREMENTS

Reach Description	Reach Number	Upbound Channel Bearing (°T)	+ = R - = L Turns	Channel Length Stat.Miles	Channel Width (ft)	(m)	Cross Track Requirements (± from C.L.)	Nav Aids Adequate
1000 Island Bridge	81	193.5	+19.5	4	800+	243+		
	82	213	+21	1.5	1080	329		
	83	234		3.5	2500	762		